

Section 1.0: Hydrologic and Sediment Control BMPs

Introduction

Controlling physical hydrologic aspects constitutes a substantial portion of the Best Management Practices (BMP) that are employed at remining sites. Reduction of the pollution load yielded from abandoned mines by remining has shown that reduction of the flow rate is the most salient factor (Smith, 1988; Hawkins, 1994). Where site conditions permit recharge to the ground-water system to be controlled through mining practices and engineering techniques, the discharge flow rate will likewise be reduced. The diminished flow rate will in a majority of cases cause a quantifiable decrease in the pollution load. Although contaminant concentrations from coal mining sources frequently exhibit an inverse relationship to flow, pollution load reductions are more commonly recorded, even when moderate increases to the contaminant concentration occur in conjunction with a discharge flow rate reduction.

BMPs that ultimately are responsible for reducing discharge flow rates include various means of reducing the infiltration of precipitation and surface waters, impeding or intercepting the movement of ground water from adjacent areas unaffected by remining activities, and providing a means to collect and rapidly remove ground water (Hawkins, 1995a). There are a battery of BMP methods that can be employed to impede recharge to mine spoil. These BMPs are subdivided into two main categories: the exclusion of infiltrating surface water and the exclusion of laterally-migrating ground water.

1.1 Control of Infiltrating Surface Water

Methods that decrease surface-water infiltration include, but are not limited to, spoil regrading (for elimination of closed-contour depressions and the promotion of runoff), installation of diversion ditches, capping the spoil with a low-permeability material, surface revegetation, and stream sealing. Prior to remining, abandoned sites commonly have unreclaimed pits and closed-contour depressions in poorly-sorted spoil that serve as recharge zones for significant quantities of infiltrating surface water. For many abandoned surface mines, the act of regrading, resoiling, and revegetating spoil significantly reduces surface-water infiltration and increases runoff just by the elimination of recharge zones and enhanced evapotranspiration. These three actions are the more commonly employed BMPs during remining operations, because they are an integral part of the remining and reclamation process. Additional means by which surface-water infiltration can be restricted are prevention of surface water infiltration by the installation of diversion ditches, stream reconstruction and sealing, and capping of the backfill with an low-permeability material.

Theory

Initially after reclamation, diffuse recharge from the surface through soil is generally well below pre-mining levels because of the destruction of soil structure, soil compaction by mining equipment, and low-vegetative growth, all of which tend to promote surface-water runoff rather than infiltration (Razem, 1983; Rogowski and Pionke, 1984). Wunsch and Dinger (1994) noted that, during re-excavation, spoil within a few inches of the surface was dry indicating little infiltration was occurring. Decreases in recharge also may be facilitated by increases in porosity in the unsaturated zone (Razem, 1984). Flow-duration curves show that after mining receiving streams have reduced base flows, which indicate that recharge is decreased (29 percent less than pre-mining levels) and surface runoff is increased (Weiss and Razem, 1984). After this initial period, as soil structure and vegetation re-establishes, diffuse recharge from the surface begins to increase. This may coincide with observed increases in hydraulic conductivity after 30 months. The slow recovery of the water table during this period may be linked to decreased recharge

shortly after reclamation and to increased effective porosity and permeability of the spoil. Increased porosity permits more of the infiltrating water to become stored within the aquifer.

Some of the recharge from the surface during this early period occurs through discrete openings or voids that are exposed at the surface (Hawkins and Aljoe, 1991; Wunsch and Dinger, 1994). Surface-exposed voids facilitating ground-water recharge also have been observed at a surface mine in central Pennsylvania that has been reclaimed for over 15 years. Surface runoff flowing across the mine surface enters the spoil through these exposed voids and flows rapidly downward via conduits to the saturated zone. This observation illustrates that these exposed voids continue to receive significant amounts of recharge long after final reclamation, re-establishment of the soil structure, and successful revegetation.

Other researchers contend that mining may improve the recharge potential from undisturbed areas (Cederstrom, 1971). Herring (1977) observed that overall recharge and surface water runoff to reclaimed surface mines in the Illinois Basin were greatly increased. Herring attributes the increased recharge to the dramatic increase in permeability of the cast overburden. Herring also observed a four-fold increase in recharge from mining one half of a watershed in Indiana. It is important to note that these two studies did not address the impact of mining on the soil horizon as discussed by Razem (1983, 1984). Once infiltrating water has passed through the soil horizon, it appears that the recharge potential is dramatically increased. In order for surface water infiltration to be prevented, the water should be intercepted before it percolates through the soil and enters the highly permeable spoil beneath.

Strock (1998) wrote:

The practical reality of this is that in ... humid areas where precipitation exceeds evapotranspiration, virtually all mine sites will receive ground water recharge and generate drainage - acidic or alkaline. That there may be no obvious springs or seeps does not imply that there is no drainage from the site. To illustrate what 15 inches (38 cm) of infiltration per year means in terms of the quantity of mine drainage which can be generated, each acre of spoil surface would produce an average flow rate of 0.75 gpm (2.84 L/min). A 100-acre surface mine, then, would yield 75 gpm (284 L/min) of ground water flow.

Unreclaimed abandoned spoil piles and ridges may permit infiltration approaching 100 percent of the precipitation falling on the site. Some of this water will be removed as direct evaporation, but most will recharge the spoil. Infiltration rates and amounts are directly related to ground slopes, particle sizes, sorting, lithology, and degree of weathering. Larger particles tend to create larger pore spaces, thus permitting rapid infiltration of substantial volumes of water. Poorly-sorted spoils likewise permit large volumes of water to infiltrate quickly, compared to well sorted fine-grained spoils. Well-cemented sandstones tend to break into and remain as large fragments, thus forming a relatively transmissive material. Conversely, many shales of the Appalachian Plateau tend to break and weather rapidly to relatively small fragments and clays creating a somewhat poorly transmissive environment (Hawkins, 1998a).

Mine spoil is a poorly sorted, unconsolidated material composed of angular particles ranging from clay-sized (less than 2 microns) to those exceeding very large boulders (greater than 2 meters). Because of the broad range of particle sizes and poor sorting, spoil tends to be highly porous and transmissive. Testing in mine spoil has recorded porosity values exceeding 15 percent for mine sites reclaimed for more than 10 years (Hawkins, 1995a). The porosity of recently reclaimed spoil may approach a spoil swell factor of 20 to 25 percent (Cederstrom, 1971). Aquifer testing in the Appalachian Plateau indicates that the transmissive properties of spoil tend to be more than two orders of magnitude (100 times) greater than that of undisturbed parent rock (Hawkins, 1995a). Some of the recharge from surface water occurs through discrete openings or voids exposed at the surface across a backfill (Hawkins and Aljoe, 1991; Wunsch and Dinger, 1994). Surface runoff from a precipitation event, flowing across the mine surface, will combine in rivulets, enter the spoil through these exposed voids, and flow rapidly downward via conduits to the saturated zone. The action of this water rapidly flowing in from the surface tends to increase the size and conductivity of these holes through the piping of finer grained sediments. In some instances, infiltrating water will reappear a short distance away (e.g., 300 feet) as a high-flowing ephemeral spring, but in most cases the water recharges the spoil aquifer and is more slowly released at perennial discharge points. Also aiding surface water infiltration is the characteristic high porosity of mine spoil, which permits rapid acceptance and storage of relatively large quantities of ground water.

Site Assessment - Backfill Testing

Spoil characteristics, such as hydraulic conductivity, porosity, and infiltration rates, are by-and-large dependent on site-specific conditions. Even with site-specific testing, these parameters can vary widely and are only predictable within a broad range. A wide range of hydraulic conductivity values (up to 3 orders of magnitude) can be recorded within a single mine site (Hawkins, 1998a). Prediction of these values prior to mining is exceedingly difficult.

Hawkins (1998a) conducted aquifer tests on several mine sites across the northern Appalachian Plateau in an attempt to predict mine spoil hydraulic properties. He found that the best correlation occurs between the age of the spoil and the hydraulic conductivity. The impacts of other factors (e.g., lithology, spoil thickness, and mining types) on spoil properties appear to be masked by a variety of factors introduced during the operation.

Given the broad range of mining types, spoil lithology and age, and other factors, it is doubtful a narrowly defined prediction model will ever be available. In addition to the aforementioned testing problems, spoil will at times exhibit turbulent flow which does not obey Darcy's Law, invalidating the aquifer testing procedures.

Materials used in sealing or grouting may require analysis to ascertain their hydraulic properties, and thus, determine suitability of use. Field testing for compaction or density may also be needed. This testing can be performed via a standard penetration test, using a penetrometer.

1.1.1 Implementation Guidelines

There are very few, if any, situations where the proper implementation of the surface water infiltration reduction BMPs discussed in this chapter will not have a positive impact toward the reduction of pollution loads. A reduction of recharge ultimately reduces discharge rate, and discharge and pollution load rates commonly exhibit a strong positive correlation. Therefore,

with a reduction in flow rate, pollution loads usually exhibit a reduction commensurate with the decreased flow (Hawkins, 1995b). Until the present, however, these BMPs have been implemented almost entirely with the intention of aesthetically-pleasing reclamation in mind. The prevention of surface water infiltration has not been a specifically targeted concern, thus the true potential to reduce discharge rates with these BMPs has not been determined.

Regrading Abandoned Mine Spoil

A significant amount of surface-water infiltration can be reduced by regrading abandoned mine spoil. Abandoned spoil piles commonly exhibit poor drainage. Closed-contour depressions and poorly vegetated surfaces facilitate the direct infiltration of precipitation and other surface waters. Closed-contour depressions permit the impounding of surface water which in turn promotes infiltration into the spoil. Rough unreclaimed spoil ridges and valleys with exposed rock fragments facilitate the direct and immediate infiltration of precipitation as it occurs. Removal of closed contour depressions, elimination of spoil ridges and valleys, and the resulting creation of runoff-inducing slopes greatly reduces surface-water infiltration into spoil.

Skousen and others (1997) observed an average flow rate reduction of 43 percent of a discharge that averaged 188 gpm at a remining operation in Butler County, Pennsylvania. The main BMP was regrading and reclamation of approximately 8.7 acres of abandoned surface mine land. A second remining operation in Butler County, Pennsylvania reclaimed about 12 acres of abandoned spoil as its primary BMP. Flow reduction of the discharges ranged from complete elimination of one, 70 percent reduction of two others, and 25 percent reduction of a fourth. While regrading and revegetation were not the exclusive BMP employed, these flow reductions are indicative of what can be achieved with these BMPs.

Regrading of abandoned mine spoil is one of the most frequently employed BMPs in the operation of remining permits. Older mining operations were not as efficient as present day operations, and could not economically excavate as deeply as more modern equipment allows. Regrading is an integral part of most remining permits. In order to achieve a minimum

reclamation standard as statutorily mandated, abandoned spoil piles are regraded to return the site to the approximate original contour or to at least achieve a more natural looking post-mining condition. In order to maximize the efficiency of this BMP, the spoil should be regraded in a manner which promotes runoff of precipitation and other surface water. This is achieved by creating slopes of a sufficient grade to induce runoff, but not to the degree that the runoff water velocity causes undue erosion.

The application of topsoil or an available soil substitute to newly regraded spoil improves the ability of spoil to impede surface-water infiltration. Several factors that directly impact changes in the infiltration rate between bare spoil and top-soiled and revegetated spoil, are lithology of the spoil material, composition, structure, roughness, and texture of the soil, density of vegetation, and surface slope. Soil freshly replaced on spoil exhibits an infiltration rate that is considerably less than that for unmined areas (Rogowski and Pionke, 1984; Jorgensen and Gardner, 1987). Therefore, it is not unexpected that the infiltration rate in resoiled spoil will be significantly below that in unreclaimed spoil. These low infiltration rates are related to the lack of soil structure, reduced root density, and the lack of other naturally occurring infiltration pathways that are present in undisturbed soils. Over time, the infiltration rate of mine soils increase. However, after four years, Jorgensen and Gardner (1987) observed that infiltration rates for mine soil were still below natural soils. Potter and others (1988) noted that significant differences between reclaimed soil properties and those of undisturbed soils still exist 11 years after reclamation.

Potter and others (1988) observed that the saturated hydraulic conductivity of reclaimed topsoil was approximately one fourth of that measured in undisturbed topsoil. Reclaimed subsoil exhibited a hydraulic conductivity about a tenth of undisturbed subsoil. Silburn and Crow observed that subsoils composed of shale and clay spoils are 10 and 100 times less permeable than from natural subsoils, respectively. Thus, runoff from reclaimed mine spoils is much greater than natural soils. The reasons for these differences are attributed to decreased percentage of large pores resulting in density increases, loss of soil structure and reduced depths to low permeability layers (Silburn and Crow, 1984).

Effective regrading of “dead” spoils, commonly an integral part of reclamation, will reduce the amount of surface water that will infiltrate into the backfill. However, there may be situations where site conditions indicate that re-affecting the spoil could cause an increase in the pollution load. These are sites where the original mining was conducted several decades earlier, the spoil has been naturally revegetated and the backfill is in a state of geochemical equilibrium. Re-affecting the site would subaerially expose a significant portion of the backfill material, allowing additional oxidation of pyritic material that was otherwise relatively stable. Remining (in this case, regrading dead spoil) could reinvigorate the production of acid-mine drainage and cause more problems than it abates. In these situations, the anticipated amount of reduced flow would have to be weighed against the projected increase in contaminant concentration.

Installation of Surface Water Diversion Ditches

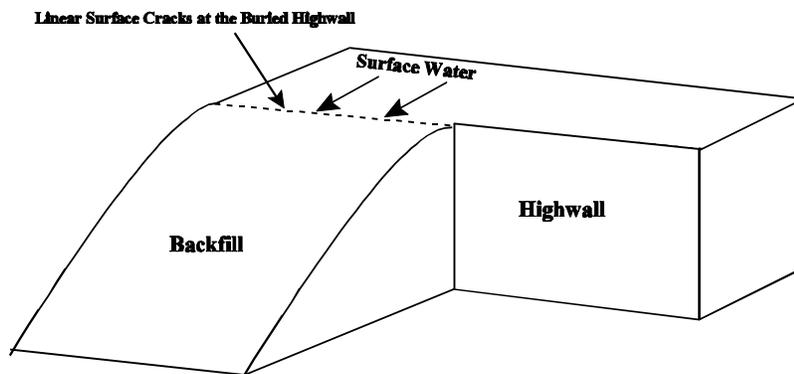
Diversion ditches can be constructed in two different locations, both of which reduce surface-water infiltration into the backfill. First, diversion ditches can be constructed above the final highwall or open pit to prevent surface water from adjacent unmined areas from entering the reclaimed site and infiltrating into the subsurface. Second, diversion ditches can be constructed within the backfill area to promote the efficient and rapid removal of direct precipitation prior to infiltration into the spoil.

Diversion ditches can be installed on top of reclaimed mine spoil to control the rate and pathway of runoff in the prevention of soil erosion. Diversion ditches also can be installed as part of a BMP plan to reduce pollution load. These ditches should be constructed to collect as much surface water as possible and to subsequently and expeditiously transport it from the site. Properly constructed (lined and sloped) ditches installed on the backfill will transport runoff from the backfill to the nearest drainage way.

A significant potential for recharge exists at the interface of the highwall and the spoil. For years and probably for decades after backfilling, spoil tends to settle, compact, and undergo other volume-reducing actions. While this settling occurs, the adjacent unmined highwall does not

appreciably change. Because of this differential settling, it is common for linear surface gaps or cracks to run along or near this interface (Figure 1.1.1a). These cracks create an ideal infiltration zone for surface water. If surface water from unmined areas can be intercepted prior to flowing across a highwall and on to the spoil, a substantial amount of infiltration can be prevented. The installation of diversion ditches above the highwall is an effective BMP to preclude recharge to the spoil from adjacent surface water runoff.

Figure 1.1.1a: Diagram of the Location of Surface Cracks Between Highwall and Backfill



Because of the transmissive characteristics of mine spoil, diversion ditches need to be lined or sealed to preclude infiltration of the water that they are designed to collect and transport away. Lining of these ditches can be performed using a variety of natural and man-made materials, such as existing on-site clays, bentonite, coal combustion wastes (CCW), sheet plastic or other geotextiles, and cement (shotcrete). Regardless of the material used to line the ditches, it will need to be durable. The integrity of these ditches should be maintained for a considerable length of time or until the mine drainage discharges no longer exceed applicable effluent standards.

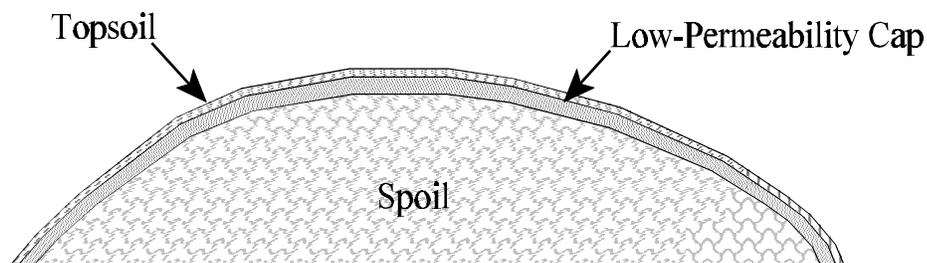
By and large, there are very few situations where properly constructed diversion ditches will not be beneficial in terms of reducing surface-water infiltration into the reclaimed site. Diversion ditches constructed above the final highwall across undisturbed ground are unlikely to be problematic in terms of leakage. The underlying subsoil and rock are less permeable than that encountered in disturbed areas. Diversion ditches constructed across reclaimed spoil are more prone to leak and allow substantial amounts of surface-water infiltration. The aforementioned porous and permeable nature of spoil can facilitate rapid infiltration of significant amounts of water over a short linear distance or at discrete points. Measures should be taken to insure the integrity of these ditches. The emplacement of some type of ditch-lining material, natural or manmade, is recommended. Where water velocities are sufficient to cause erosion, an erosion-resistant material should be placed as a cover for the liner material.

Lining diversion ditches with a relatively impervious material reduces the amount of infiltration through the bottom of the ditch, thus reducing recharge to the underlying strata. Reducing recharge to areas adjacent to reclaimed mines can indirectly reduce the amount of recharge to the mine spoil. When the adjacent strata receives increased recharge, some of this ground water will flow toward and enter the spoil. Therefore, if surface-water infiltration from the diversion ditch is impeded, recharge to adjacent spoil aquifers may also be reduced.

Low-Permeability Caps or Seals

There have been sporadic studies performed to determine the efficiency of sealing or capping the surface of backfilled surface mines. The intention of sealing or capping is to preclude area-wide surface-water infiltration by placing a low-permeability cap over the backfill material, before the soil is replaced (Figure 1.1.1b). Because of the large surface area to be covered and the generally low profit margin at remining sites, the capping material should be readily available and inexpensive to make this BMP a viable option. Capping materials generally should be composed of a locally-available waste product, such as pozzolonic (self-cementing) CCW or a naturally-occurring clay within a short hauling distance.

Figure 1.1.1b: Schematic Diagram of a Cap Installed on a Reclaimed Surface Mine



The installation of low-permeability caps over the top of mine backfills can be an effective BMP for reducing surface-water infiltration. However, installation of these caps can be an expensive operation. Before approving the use of this BMP, the reviewer needs to ascertain whether it is economically feasible. The reviewer also needs to determine that the capping materials are readily available and of sufficient quality to complete the operation. Additionally, because mine spoil continues to subside with time, as has been observed beyond ten years after reclamation, the cap should be made to withstand the expected subsidence as much as possible.

In order to prevent the movement of water and atmospheric oxygen, Broman and others (1991) determined that capping materials need to have a hydraulic conductivity of 5×10^{-9} m/s or less. Broman and others developed a mixture of 35 percent biosludge from a paper mill and 65 percent coal fly ash. Lundgren and Lindahl (1991) specified a hydraulic conductivity of 1×10^{-9} m/s or less for a capping material for waste rock piles in a copper-producing area of Sweden. They successfully used a grouting cement-stabilized coal fly ash material, with a hydraulic conductivity approximately one order of magnitude lower than this specified value. Hydraulic conductivity values ranging from 10^{-10} to 10^{-12} m/s were recorded by Gerencher and others (1991) for shotcrete used to cap and seal waste rock dumps in British Columbia. Based on these studies, the hydraulic conductivity values necessary to create an effective cap are in the range of 10^{-9} to 10^{-10} m/s. These values are similar to values recorded for extremely impervious igneous rock, such as dense unfractured basalt (Freeze and Cherry, 1979). Spoil, on the other hand, is substantially more transmissive exhibiting a median hydraulic conductivity of 2.8×10^{-5} m/s. However, the hydraulic conductivity of spoil exhibits a very broad range, 10^{-9} to 10^{-1} m/s, depending on the parent rock lithology and other geologic- and mining-related factors (Hawkins, 1998a).

A 20 hectare mine site in Upshur County, West Virginia was covered with PVC sheeting in an effort to reduce the pollution load. The result was a 50 to 70 percent reduction of the acidity load. Even though additional BMP techniques (e.g., special handling, lime and phosphate addition) were employed at this site and may have contributed some to the acid load reduction, the bulk of the pollution load reduction appeared to be directly related to the subsequent flow reduction (Meek, 1994).

A layered-composite soil cover was used to cover waste rock piles near Newcastle, New Brunswick, Canada in an attempt to preclude infiltration of atmospheric oxygen as well as water. The system consisted of a sand base overlain by compacted glacial till covered with sand and gravel. The top layer of cover consisted of 10 cm of well-graded gravel to prevent erosion. This system permitted between 1 and 2 percent of precipitation falling on the site to infiltrate into the

waste rock below the cap. The cap's low-permeability material was glacial till with a hydraulic conductivity of 1.0×10^{-8} m/s (Bell and others, 1994).

Yanful and others (1994) constructed a cover for tailings piles in Canada to prevent the infiltration of surface water and atmospheric oxygen. A 60 cm compacted clay layer was placed between two 30 cm sand layers. The clay had an initial hydraulic conductivity of 1.0×10^{-9} m/s, which did not change during the 3 year monitoring period. A thin gravel layer was placed over the top of the cap for protection. This cover excluded over 96 percent of the total precipitation from infiltrating into the tailings.

These studies indicate that if a cap is placed on top of a reclaimed backfill, a significant reduction of surface-water infiltration can be achieved. For example, if a hypothetical unreclaimed and unvegetated site permits infiltration of 75 percent of the precipitation (this number is likely higher) and continues to allow 35 percent infiltration after it is regraded, the addition of an effective cap should decrease the infiltration rate to between 2 and 4 percent. Let us assume that a 100 acre site receives 40 inches of precipitation per year and all of the infiltrating water discharges at one point. In the unreclaimed state, the average discharge rate would be 155 gpm. Once regraded the discharge will yield approximately 72.3 gpm. If a cap is installed the discharge rate should be reduced to 8.3 to 12.4 gpm. If the initial acidity concentration is 120 mg/L, the loading rate for the unreclaimed site would be 225.4 lbs/day. However, with regrading and cap installation, even if the acidity concentration increased by 10 percent to 132 mg/L, acidity loading would still show an overall decrease to a range of 13.3 to 19.8 lbs/day or 91.2 to 94.1 percent.

Revegetation

Revegetation of mine spoil can dramatically reduce the amount of surface water that would otherwise eventually make it to the underlying ground-water system. Vegetative cover also can decrease the amount of atmospheric oxygen that can enter the subsurface, because biological activity in the soil, such as decay of organic matter, can create an oxygen sink. A well developed

soil with a dense cover of vegetation can retain a significant amount of water. Eventually, this water evaporates or is transpired by the plants and does not recharge the spoil aquifer. Because this BMP is a statutory requirement of all mining permits, it is one of the most frequently employed. However, attempts to specifically tailor the vegetative cover to maximize evapotranspiration are rare to nonexistent.

Evapotranspiration of surface water entering mine spoil will be enhanced as the vegetative cover is increased (Strock, 1998). A thick forested area will permit more than twice as much evapotranspiration (35 inches per year) as barren rocky ground (15 inches per year) in the same area (Strock, 1998). The actual water loss depends on several factors including density, type of plants, and length of the growing season.

Revegetation of a reclaimed mine will in most cases be beneficial toward reducing surface-water infiltration. Caution should be used to prevent vegetative cover from providing conductive avenues for surface-water infiltration. In some cases, the root systems of plants will create areas where water can infiltrate in to the spoil. However, a lush vegetative growth may allow for greatly increased evapotranspiration rates that can offset the increased infiltration along root zones.

Stream Sealing

The sealing of streams reconstructed across backfill areas is intended to preclude direct infiltration into the spoil. The increased permeability and porosity of spoil by comparison to undisturbed strata promotes streams that have been reconstructed in mine spoil to lose water to the underlying aquifer. The water table in surface mine spoil is commonly suppressed compared to the water table at the site prior to mining and/or in adjacent unmined areas (Hawkins, 1995a). A hydraulic gradient from the reconstructed stream to the suppressed underlying water table is frequently present, thus facilitating infiltration. Therefore, reconstruction of these streams should be conducted with the assumption that they will leak unless sealed or lined.

The primary and probably most inexpensive method of sealing streams is with plastic sheet lining. Shotcrete can also be used for lining limited sections of stream beds in a relatively cost effective manner. One of the problems associated with plastic lining is that the plastic sheeting eventually breaks down chemically and ruptures or is punctured by sharp rock fragments.

Stream sealing also has been performed by excavating and emplacing a clay liner along the stream reach (Ackman and others, 1989). In this case, the stream was disrupted by subsidence from a shallow abandoned underground mine. The effectiveness of the clay seal was less than 100 percent. The section of stream that was clay lined exhibited a 4 percent loss of flow over approximately 170 feet, whereas, the preceding section of stream exhibited an 8 percent flow decrease over a similar distance.

Another method of stream sealing involves injecting polyurethane to grout targeted sections of streams. Similar grouting has been successfully conducted on losing streams situated over the top of abandoned underground mine workings. In these cases, the underlying mine was relatively shallow (25 to 50 feet) and losing stream sections were located by use of electromagnetic terrain conductivity surveying equipment. Once located, zones of significant infiltration were targeted for grouting (Ackman and Jones, 1988). Given the length of stream that would require grouting and the high porosity of the spoil, it is doubtful that polyurethane grouting would be economically viable for most remining operations.

Stream sealing as a BMP is appropriate only where a section of a stream is mined through and subsequently reconstructed. Like diversion ditches that cross a reclaimed mine, these streams should be rebuilt in such a manner that they do not leak water into the subsurface. The stream bed should be underlain with a liner material to preclude surface water infiltration. However, erosion-resistant material should be placed over the top of the liner to prevent future liner breaching.

Design Criteria

The design and implementation plan of BMPs intended to reduce the infiltration of surface water into mine spoil and adjacent undisturbed areas depends a great deal on site conditions (i.e. amount of precipitation, location of surface water streams or drainage areas, original contour, indigenous vegetation, soil type, and readily available materials). Recommended design criteria for the implementation of surface-water infiltration control BMPs are included in the following list. This list is by no means all-inclusive. Permit writers, regulatory authorities, and designers should consider all site conditions with the intent of implementing the most cost effective means of reducing pollutant loading during remining operations.

Regrading

- Promote controlled runoff of precipitation and other surface waters
- Return the site to the approximate original contour
- Performed along the contour to minimize erosion and instability

Diversion Ditches

- Divert runoff away from disturbed areas
- Promote rapid runoff from disturbed areas
- Adequate to pass the peak discharge of a defined storm event such as a 2-year, 24-hour storm (temporary ditches) or a 10-year, 24-hour storm (permanent ditches)
- Diversion ditch construction in landslide prone areas or where severe erosion is possible should be performed with extreme care, if at all

Caps or Seals

- Use readily available materials (e.g., on site clays or CCW)
- Material with hydraulic conductivity of 10^{-9} m/s or less
- Should be able to withstand anticipated subsidence without breaching

Revegetation

- Root systems should retain water and not provide infiltration pathways
- Select local and native plant species that will thrive and create a lush cover

Stream Sealing

- Use chemically inert materials that are not prone to erosion or puncture damage
- Use readily available materials (e.g., on-site clays or CCW)

1.1.2 Verification of Success or Failure

Verification that BMPs have been properly and completely implemented during remining operations is crucial to effective control or remediation of pollutant loading. In other words, monitoring should ensure that the as-built product is the same as that originally proposed by the operator and approved by the regulating authority. The importance of field verification of all aspects of a BMP cannot be overstated. It is the role of the mine inspector to enforce the provisions outlined in the permit. The mine inspector does not need to be present at all times to assess the amount of regrading for dead spoils, the elimination of closed-contour depressions or revegetation. The completion of these tasks should be evident from visual inspection or if required, from a survey of the area.

The actual installation of diversion ditches or stream replacements should be self evident from a visual inspection. However, whether the ditch or stream was properly constructed and will not leak requires a bit more work on the part of the mine inspector or hydrologist. If a liner was prescribed for proper stream installation, the inspector can require weigh slips or receipts for material brought into the site. If on-site material is to be used, a marked material stock pile can be required. An inspector also can require notification of liner installation and completion dates. Failure of a ditch or a stream to hold water can be determined by conducting flow measurements. If the flow shows a significant decrease (e.g., outside the known error of the flow measurement method) or disappears altogether, there is an indication that water is infiltrating and recharging the backfilled site.

Determining the implementation level of some of the BMPs discussed in this chapter after the fact is not always an easy procedure. Verification that a capping seal was installed properly, without being present during the operation, can be difficult. However, if the capping material is trucked in from an outside source, weigh slips or receipts can be obtained to confirm the amount of material used. If on-site material is to be used, a marked stockpile of the material can be required. Given the amount of work involved in spreading and compacting, it is likely a mine inspector will visit the site at least once during the capping process. If there is great concern that the cap will not be properly installed, the permit can be conditioned to require notification of the mine inspector at predetermined salient points during the procedure.

The efficiencies of BMPs need to be monitored in order to improve and effect future refinements of the processes. Not only does the type of BMP need to be assessed, but the scope and degree of BMP implementation needs to be related to the degree of improvement (e.g., flow or pollution load reduction). The mechanism to determine the effectiveness of BMPs discussed in this chapter is similar to any abatement procedure research project. In the case of these surface water control BMPs, a significant portion of the monitoring will consist of measuring the flow rates of discharges emanating from the site. It is fully realized that the locations of discharges may, and frequently do, move from their pre-remining locations. Therefore, a hydrologic-unit approach is recommended. The mine site should be divided into hydrologic units, that is, portions of the mine that contribute to one or more discharges. Discharge data (flow and/or loading rate) can be mathematically combined to permit pre- versus post-mining comparisons.

Given the nature of mine spoil and the time that it takes for a water table to re-establish and reach equilibrium, post-mining monitoring may need to continue for at least 3 to 5 years. In eastern Ohio, water-table re-establishment at three reclaimed surface mines was observed to be nearly complete approximately 22 months after reclamation was completed (Helgesen and Razem, 1980). Recovery of the water table after mining may take 24 months or longer in Pennsylvania (Hawkins, 1998b). The rate of water-table recovery is related to several factors including precipitation, infiltration and discharge rates, porosity, topography, and geologic structure. Additionally, short-term changes in flow and/or contaminant concentration commonly occur

during the initial 1-3 years after backfilling because of substantial physical and chemical flux within the spoil aquifer. During this period, the water table is re-establishing and the spoil is undergoing considerable subsidence, piping, and shifting. Sulfate salts, created by oxidation when cast overburden is exposed to the atmosphere during mining, are flushed through the system (Hawkins, 1995b). It is important to monitor these sites beyond the initial re-establishment period, in order to accurately assess the true changes due to remining and BMP implementation. The length of the post-mining monitoring period may vary from site to site depending on climatic (e.g., precipitation) and hydrogeologic (spoil porosity and permeability, topography, etc.) conditions, and should be at the discretion of the professional in charge of project oversight.

Implementation Checklist

Monitoring and inspection of BMPs, in order to verify appropriate conditions and implementation, should be a requirement of any remining operation. Though BMP effectiveness is highly site-specific, it is recommended that implementation inspections of hydraulic control BMPs include the following:

- Measurement of flow and sampling for contaminant concentrations (before, during, and after mining)
- Monitoring should continue well beyond initial water table re-establishment period (e.g., about 2 years after backfilling)
- Assessment of hydrologically connected units as well as individual discharges
- Review or inspection of sealing-material weigh slips, receipts, or marked stockpiles
- Review of implementation initiation and completion dates
- Assessment of any deviation from an approved implementation plan
- Inspection of salient phases of the BMP implementation
- Inspection of diversion ditches, caps and seals for leakage
- Inspection of vegetation for viability

1.1.3 Case Studies

Presented below are results from three completed remining operations for which a significant portion of the site had dead spoils regraded, closed-contour depressions eliminated, and more natural runoff-inducing slopes created. It is important to note that the full potential of these BMPs may not have been realized because regrading was performed primarily as part of the perfunctory reclamation process. These BMPs were not necessarily implemented with the minimization of surface-water infiltration as a primary intention. Evaluation of these sites may tend to underestimate the potential for infiltration reduction that can be achieved. Minor implementation modifications can dramatically affect efficiency. Future efforts which employ these BMPs to their greatest potential should be closely monitored and analyzed in an attempt to ascertain true BMP efficacy and to develop methods for fine tuning and improvement.

There are several factors that make pre-mining versus post-mining comparison difficult. One of the main pitfalls in comparing the discharge rates is the assumption that the pre- and post-mining periods have had similar precipitation preceding the measurements. Precipitation amount, duration, and intensity can vary widely from event to event, season to season, and year to year, serving to complicate pre- to post-mining comparisons. This is especially true when the sampling periods before and/or after mining are relatively short (e.g., a year or less). Another complicating factor is that post-mining sampling often will include a period of time when the water table is re-establishing and much of the infiltrating water is going into storage. Under ideal conditions, an evaluation of flow reduction from BMPs discussed in this chapter would entail similar climatic conditions, preclude data collected during water table re-establishment, and include several years of pre- and post-mining monitoring. These criteria are seldom met in real-world situations. The location of the pre-existing discharges commonly move because of the physical disruption of the yielding aquifer and ground-water flow paths, and the change of the flow system from a fracture-flow dominated system to a dual-porosity system as exhibited in mine spoil. These caveats and potential problems should be considered while reviewing the case studies below.

Case Study 1 (Appendix A, EPA Remining Database, 1999, PA(6))

This mine was located in Armstrong County, Pennsylvania where the remining was performed on abandoned surface mines in the Upper Freeport and Lower Kittanning coal seams. All 24.8 acres of abandoned surface mined land within the permit boundary was reclaimed by the operation. According to the permit application, the total area to be affected by mining operations was 126.5 acres. The operation also eliminated 1,700 feet out of a possible 2,600 feet of highwall. Originally, two remining discharge points were included in the permit. However, a third discharge point was added later. The BMPs listed in the permit included regrading of abandoned mine spoil (24.8 acres), underground mine daylighting (5 acres), special handling of acid-forming materials, and revegetation. The most predominant BMP component by far was the regrading. The site was completed in August of 1996 and post-mining water quality data has been collected since. A synopsis of the data is shown in Table 1.1.3a.

The changes in flow rates from remining of this site are somewhat inconsistent. Discharge point MD-2 exhibits a statistically significant increase in flow, but the acidity and iron loads are not significantly higher. This is caused by decreases in concentrations and a relatively broad range of values, resulting in a wide 95 percent confidence interval about the median, as is commonly associated with mine drainage. Discharge points C-3A and C-17A exhibit only very minor differences in the discharge rate after remining. The acidity concentration decreases caused the median acidity loads to be substantially lower, but only the decrease in the median acidity load of C-17A is statistically significant.

Table 1.1.3a: Synopsis of Water Quality Data at Case Study 1 Site

Parameter	Discharge Points					
	MD-2		C-3A		C-17A	
	Pre-Remining	Post-Remining	Pre-Remining	Post-Remining	Pre-Remining	Post-Remining
Sample Number (n)	22	22	24	22	6	17
Flow (gpm)	2.4	27.1	14.2	16.3	12.5	9.1
Acidity Load (lbs/day)	1.93	4.76	16.17	0.75	8.56	0.07
Iron Load (lbs/day)	0.0016	0.0044	0.09	0.10	0.003	0.003
Sulfate Load (lbs/day)	5.57	85.78	23.15	60.01	21.06	25.45

All numbers are median values.

The lack of better flow reduction may predominantly be due to precipitation differences during the two comparison periods and, to a lesser degree, to a rerouting of ground-water flow paths. The reclamation area comprised a small amount (slightly under 20 percent) of the total area to be disturbed by remining. In addition, the post-remining period is relatively short (less than 2 years) in terms of allowing complete re-establishment of the water table and post-remining stabilization of the entire hydrogeologic system. Additional monitoring of the site will likely illustrate more clearly the true impacts of regrading and revegetation.

Case Study 2 (Appendix A, EPA Remining Database, 1999, PA(7))

This mine was located in Clearfield County, Pennsylvania. Remining was performed on abandoned surface mines in the Upper Freeport and Lower Kittanning coal seams. Ten acres (32 percent) of the 30.8 acres of abandoned surface-mined land within the permit boundary was reclaimed by the operation. Of the 101.1 acres of abandoned underground mines on the Lower Freeport coal, 17.3 acres (17 percent) were daylighted during the remining operation. According to the permit application, the total area to be affected was 139.3 acres. Two remining discharge points were included in the permit. The BMPs listed in the permit included regrading of abandoned mine spoil (10 acres), underground mine daylighting (17.3 acres), sealing of exposed mine entries, special handling of toxic materials, and revegetation. The predominant BMP

components were regrading, revegetation, and daylighting. The site was completed in May of 1996, and was assessed using monthly water-quality data collected through August 1997. A synopsis of the data is shown in Table 1.1.3b.

Table 1.1.3b: Synopsis of Water Quality Data at Case Study 2 Site

Parameter	Discharge Points			
	MD-12		MD-13	
	Pre-Remining	Post-Remining	Pre-Remining	Post-Remining
Sample Number (n)	44	16	47	16
Flow (gpm)	0.55	0.40	31.6	35.9
Acidity Load (lbs/day)	2.48	0.59	176.2	133.7
Iron Load (lbs/day)	0.047	0.006	9.99	6.31
Sulfate Load (lbs/day)	2.87	2.65	273.79	289.8

All numbers are median values.

Analysis of the data indicate that the flow rates of the two discharges were not significantly changed by the remining (regrading and revegetation); there is no statistical difference. The acidity and iron concentrations at MD-12 were significantly reduced, but the lack of significant flow changes prevented concomitant acidity and iron load reductions. Figures 1.1.3a and 1.1.3b illustrate an example of these observations. The lack of overlap of the notches indicating the 95 percent confidence intervals about the medians indicate that the medians of acidity data before and after remining operations are significantly different, with a definitive decrease in acidity following remining site closure.

Figure 1.1.3a: Acidity Concentration at Discharge Point MD-12 Before and After Remining

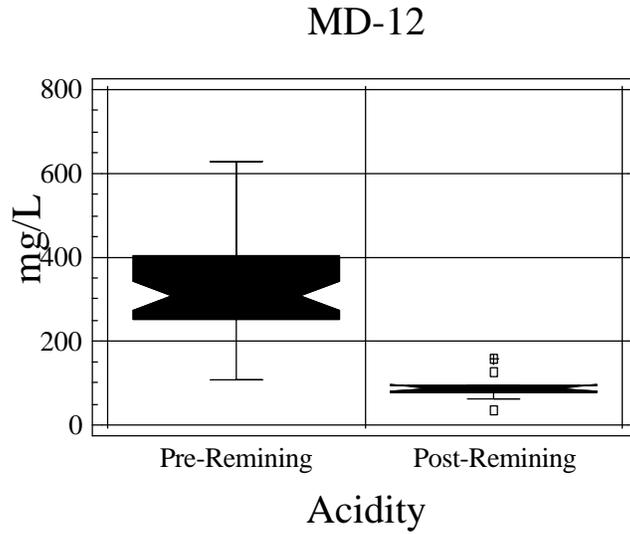
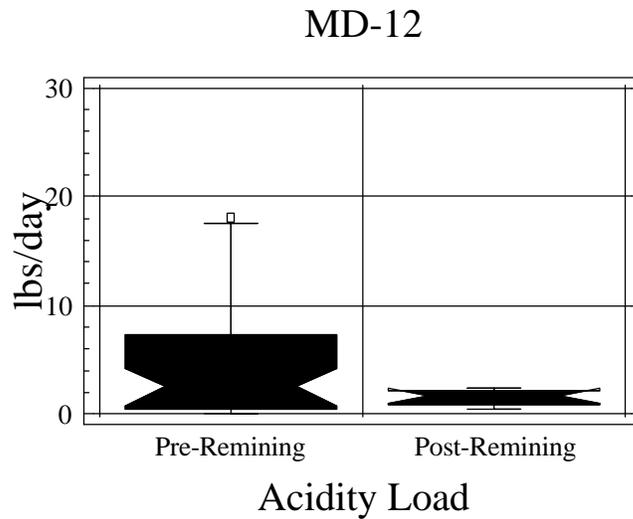


Figure 1.1.3b: Acidity Load at Discharge Point MD-12 Before and After Remining



Some of the same caveats that apply to Case Study 1 also apply to this site. The climatic differences (e.g., precipitation) for the two sampling periods should be considered as part of the overall evaluation of flow changes due to remining. For example, the period of pre-remining sampling (12/86 through 9/89) averaged 2.83 inches of precipitation per month, while the post-remining period (5/96 through 8/97) averaged 3.36 inches of precipitation per month. This is an increase of about 19 percent. The precipitation values were compiled from the Pittsburgh International Airport which is approximately 90 miles southwest of the site. However, the data can be used for the general precipitation trends during pre- and post-remining sampling periods at this site. The increase in flow from the combined discharges (about 13 percent) is not commensurate with the recorded precipitation increase. Additionally, the post-remining period is relatively short (less than 2 years) in terms of allowing complete re-establishment of the water table and post-remining stabilization of the entire hydrogeologic system. Additional monitoring of the site over a longer time period and with similar precipitation amounts will likely clarify the true impacts of regrading and revegetation.

Case Study 3 (Appendix A, EPA Remining Database, 1999, PA(10))

This site is located in Somerset County, Pennsylvania. Remining was conducted on the Lower Bakerstown coal seam. According to the permit application, a total of 85.8 acres was to be affected by the operation and 48.8 acres of coal removed. BMPs employed at this site included regrading of abandoned spoils, alkaline addition, hydrologic controls, revegetation, and scarification of the calcareous pavement (seat rock). Of the 32.2 acres of abandoned mine lands within the permit boundary, 15.6 acres, or 48 percent, were to be reclaimed. Approximately 1,800 feet (84 percent) of a total of 2,150 feet of abandoned highwall was eliminated. The alkaline addition rate was 3 tons per acre applied at the interface of the spoil and the topsoil. Hydrologic controls consisted of a clay barrier placed between remining operations and adjacent unreclaimed areas. The seat rock was found to be alkaline and was scarified to increase the surface area of the alkaline material exposed to ground water. Reclamation was completed by

November of 1995 and monitoring has continued since that time. Table 1.1.3c is a synopsis of the flow and loading data for this site.

Table 1.1.3c: Synopsis of Flow and Pollutant Loading Data at Case Study 3 Site

Parameter	Discharge Points									
	SP-10		SP-11		SP12		SP-18		SP-23	
	Pre-Remining	Post-Remining	Pre-Remining	Post-Remining	Pre-Remining	Post-Remining	Pre-Remining	Post-Remining	Pre-Remining	Post-Remining
Sample Number (n)	8	34	8	34	8	34	8	35	4	34
Flow (gpm)	7.47	5.15	11.3	3.0	1.0	0.7	0.88	1.20	0	0
Acidity Load (lbs/day)	2.72	8.18	20.5	7.4	1.04	0.95	0.31	1.97	0	0
Iron Load (lbs/day)	0.006	0.008	0.03	0.01	0.004	0.003	0.003	0.004	0	0
Sulfate Load (lbs/day)	21.6	49.4	71.1	57.2	11.3	6.06	3.04	9.51	0	0

All numbers are median values.

This site exhibited an accumulative discharge median flow reduction of 10.6 gpm or slightly over 51 percent. However, only SP-11 exhibited a statistically significant flow reduction on an individual basis. According to the precipitation history from the Pittsburgh International Airport, precipitation during the two sampling periods was dissimilar, with precipitation during the post-remining period (a mean of 3.29 inches per month) being about 15 percent below the background sampling period (a mean of 3.85 inches per month). Roughly 15 percent of the flow reduction may be attributable to reduced precipitation, but the remainder appears to be related to regrading, highwall elimination, and revegetation. The same caveats discussed in Cases 1 and 2, on using precipitation data from a site somewhat removed from the actual mine sites, apply here. These results illustrate that substantial flow reduction (approximately 35 percent) may be realized by a 50 percent reduction in abandoned mine lands, even with additional mining of virgin areas (49 acres) occurring in conjunction with the operation. The post-mining monitoring period is considerable, exceeding three years, but additional monitoring is required to determine whether the trends observed are genuine and can be expected to continue. Additional flow reduction may

be possible if regrading and revegetation are designed specifically with the intent of preventing surface-water infiltration, rather than solely with the intent of returning the site to an aesthetically-pleasing approximation of the original pre-mining contours and conditions. Specific operations to reduce surface-water infiltration may include, but are not limited to, additional compaction of the spoil to reduce permeability, final slopes that may differ from the approximate original contour but are more efficient in promoting runoff, and plants that promote runoff and/or utilize substantial amounts of the water that does manage to infiltrate into the soil horizon.

Even with the aforementioned reductions in discharge flow, two of the discharges (SP-10 and SP-18) exhibited a statistically significant increase in median acidity and sulfate loads. This difference is caused by substantially higher acidity and sulfate concentrations after reclamation. Discharge points SP-11 and SP-12 also exhibit significantly increased concentrations of acidity, but the reduced flows prevent the median loadings from being significantly different from the baseline levels. This indicates that the site may be producing more acidity, but the reduced flow moving through the site has prevented the combined discharge acid load from exceeding baseline.

Geochemical conditions within this reclaimed operation have worsened, or become more acidic. The causes of this possible failure will be discussed in detail in the section on alkaline addition.

To obtain a more definitive determination of the efficiency of regrading and revegetation to reduce discharge rates, additional studies are needed on sites where these BMPs are employed specifically to preclude surface-water infiltration. The case sites discussed above utilized these BMPs during remining operations, but they did not specifically design or implement them to minimize infiltration of surface water. Thorough evaluation of these studies also requires site specific precipitation data for background sampling as well as post-mining sampling periods. A sufficient post-mining sampling period of at least 3-5 years, depending on climatic and site-specific conditions, is required to permit a true assessment of BMP efficiency. With these data, prediction of load reduction based on the amount of regrading, revegetating, and other BMPs may be possible.

1.1.4 Discussion

The BMPs discussed in this chapter, when properly employed under the right conditions, will successfully reduce the infiltration of surface waters and should subsequently reduce the discharge yield. However, these BMPs cannot be viewed as a panacea for all pre-existing problems at a site. There are limits to what can be physically achieved and/or economically attempted. The two lists below (Benefits and Limitations) include, but are not limited to, what can and cannot be expected of these BMPs.

Benefits

- Reduces pollution loading from abandoned mine land
- Establishes a hydrologic balance to site
- Restores land to approximate original contour and creates an aesthetically pleasing post-remining configuration
- Requires little additional cost to the operation because they are often already implemented as a statutory requirement during remining operations

Limitations

- Current implementation of hydraulic control BMPs focuses primarily on reclamation. A complete evaluation of the effectiveness for pollution prevention, in terms of reducing the discharge rate, is needed.
- Careful consideration should be made to the implementation of surface-water control BMPs in areas abandoned for long periods or with some degree of natural remediation (e.g. stabilized spoil, natural vegetative cover).
- Complete exclusion of infiltrating surface waters is not likely, therefore the discharges will not be entirely eliminated.

Efficiency

Analysis of completed remining sites in Pennsylvania (Appendix B, PA Remining Site Study) indicated that at sites with regrading as a BMP, 46.1 percent of 154 discharges were eliminated

or were significantly improved in terms of acidity loadings. Over half the discharges (53.2 percent) were unchanged and less than one percent (0.6 percent) were significantly degraded with respect to acidity loadings.

For iron loadings, 42.3 percent of 137 discharges were eliminated or significantly improved from remining. Over half (52.6 percent) of the discharges were unchanged, while 5.1 percent showed significant degradation for iron loadings.

The manganese loadings for 39.6 percent of the 111 discharges were significantly improved or eliminated, while 52.3 percent were unchanged. The manganese loading failure rate was the highest for the parameters analyzed, with 8.1 percent significantly degraded. This has been a common trend for all the BMPs. Manganese loadings exhibited the highest failure rate (9.0 percent for 155 discharges) regardless of the BMP employed.

The bulk (60.7 percent) of the aluminum loadings for 84 discharges were unchanged, while 36.9 percent of the discharges were significantly improved or eliminated. Discharges that were significantly degraded, in regards to aluminum loadings, amounted to 2.4 percent.

1.1.5 Summary

Studies have shown that the extent of pollution reduction from remining is largely dependent on reducing the discharge rate, which in turn is dependent on controlling the infiltration of surface water into the backfill. The commonly-observed positive correlation between flow and loading rates illustrates the close relationship between the two. BMPs that are designed and implemented to prevent surface-water infiltration will be successful in reducing the pollution load.

The case studies above illustrate that regrading and revegetating can yield mixed results unless differences in precipitation rates are taken into account and the post-mining monitoring period is of sufficient length to accurately reflect site conditions. However, it is well known that these BMPs, when properly implemented, will reduce the contaminant load from remining operations.

1.2 Control of Infiltrating Ground Water

Methods to control the lateral infiltration (recharge) of ground water into remining sites from adjacent mines and undisturbed strata include, but are not limited to, daylighting of underground mine workings, sealing exposed mine entries, auger holes, highwalls and pit floors, and installing diversion drains, vertical highwall (chimney) drains, pit-floor drains, grout curtains and diversion wells. These BMPs are designed to work in one of two ways to reduce the ultimate discharge flow rate: (1) to preclude or divert the lateral movement of ground water; and (2) to intercept and collect laterally-migrating ground water and channel it away from the backfilled areas. These BMPs are effective singly or when used in conjunction with others, but are seldom used alone during remining operations.

Currently, these BMPs are being used as a part of the general mining and reclamation processes, but they are not being implemented with ground-water handling as the primary concern. Therefore, the results of the case studies (discussed below) and other remining data (Appendix B: Pennsylvania Remining Site Study) may tend to underestimate the potential for lateral infiltration reduction that can be achieved. Minor implementation modifications toward ground-water handling can dramatically effect the efficiency of these BMPs with little additional time or expense introduced.

Theory

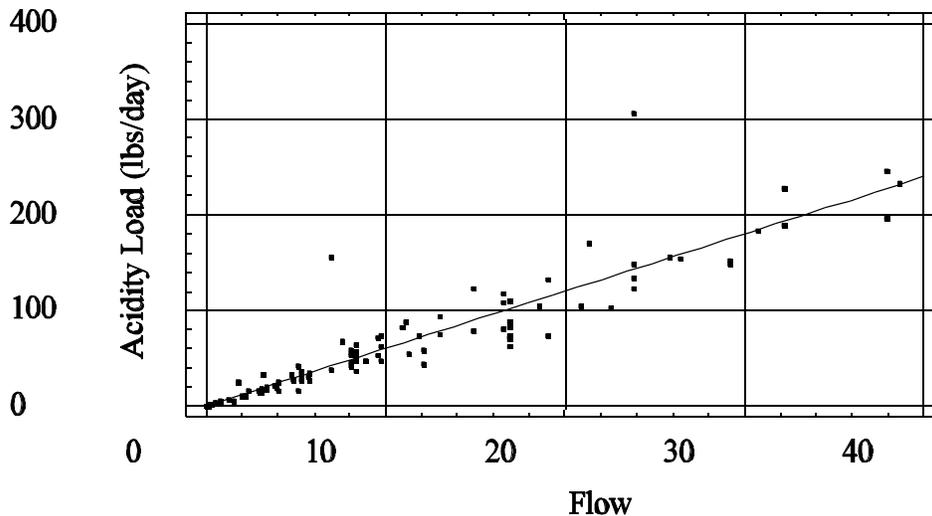
Ground-water modeling of reclaimed surface mines has shown that a substantial portion of ground-water infiltration into mine spoil comes from adjacent areas. Infiltration from adjacent areas can originate from other surface mines as well as from unmined strata. The nature of this lateral recharge can be continuous or episodic. Adjacent areas tend to permit lateral ground-water movement somewhat continuously under baseflow conditions, long after the last precipitation event. However, rapid, high-volume lateral recharge also can occur immediately

following significant rainfall events (Hawkins and Aljoe, 1990). Fractures in the adjacent strata can yield substantial amounts of water during or shortly after significant precipitation. The BMPs discussed in this section need to be able to accommodate this bimodal, lateral ground-water infiltration.

Unlike many of the BMPs implemented to prevent surface-water infiltration, most of the BMPs for preventing lateral ground-water movement are implemented on and above standard reclamation practices. These BMPs tend to be more labor and material intensive than standard reclamation practices, and therefore, can be more costly. One exception is underground mine daylighting, which is performed as a consequence of the remining process. However, the time and effort required to clean the waste rock from around the remaining coal pillars entails additional cost during mining, the percentage of coal recovery is less than that for virgin areas, and additional acid-forming materials should be special handled. Some of the BMPs discussed in this section are mandated by regulation, such as sealing of auger holes and exposed mine entries.

The effectiveness of many of the ground-water control BMPs relies largely on the use of proper engineering techniques. As with BMPs implemented for the prevention of surface-water infiltration, there are very few situations where these BMPs will fail. If the ultimate discharge flow rate is reduced through reduced lateral infiltration, there is a high probability that the pollution load will be diminished. Figure 1.2a shows the strong flow-versus-pollution-load correlation commonly exhibited by mine drainage discharges. There are hydrogeologic conditions where some of these BMPs could exacerbate the production of acid mine drainage (AMD). In these cases, the BMP should be eliminated or modified to prevent additional pollution. In situations where the BMP is an integral part of the entire operation (e.g., daylighting), additional BMPs will need to be added or designed to compensate for possible deleterious side effects of the others.

Figure 1.2a: Typical Correlation Between Discharge Flow and Pollutant Loading in Mine Drainage Discharges (Appendix A, EPA Remining Database, 1999 PA(6), MP-A)



Site Assessment

Assessment of spoil characteristics is site-specific for each operation. Even with on-site testing, spoil hydraulic parameters can be highly variable. Hawkins (1998a) observed that hydraulic conductivity can range widely (up to 3 orders of magnitude) within a site. This makes prediction of spoil characteristics prior to mining extremely difficult. However, there are some general conclusions that can be drawn about mine spoil.

Hawkins (1998a) conducted aquifer tests on several mine sites across the northern Appalachian Plateau in an attempt to predict mine spoil hydraulic properties. He found that the best correlation occurs between the hydraulic conductivity and age of the spoil. The impacts of other factors (e.g., lithology, spoil thickness, and mining type) on spoil properties appear to be masked by a variety of factors introduced during the operation.

Given the broad range of mining types, spoil lithology and age, and other factors, it is doubtful a narrowly-defined prediction model will be available. In addition to the aforementioned testing problems, spoil will at times exhibit turbulent flow which does not conform to Darcy's Law and causes aquifer-testing procedures to become inapplicable.

Prior to the engineering and installation of highwall and pit floor drains, an assessment as to the amount of ground water to be collected and piped needs to be made. This determination can be performed by empirical testing of observed recharge while the pit is open or can be performed by conducting a hydrologic budget exercise. The hydrologic budget will require, at a minimum, knowledge of the size of the recharge zone, precipitation and evapotranspiration rates, storage capacity, and aquifer characteristics.

Materials used in sealing or grouting may require analysis to ascertain the hydraulic properties, and thus, the suitability of use. Field testing for compaction also may be necessary. This testing can be performed via a standard penetration test, using a penetrometer.

Assessment of ground-water diversion (interceptor) wells may require aquifer testing. Performing a constant-discharge test while monitoring other wells will yield insight as to the efficiency of these wells. Aquifer testing will also yield data on well and aquifer interconnection.

1.2.1 Implementation Guidelines

Daylighting of Underground Mines

Underground mining has been conducted in some areas of the United States for over 200 years. Although limited surface mining was conducted in the early part of the 20th century, surface mining did not become prominent until after the Second World War. Surface mining into higher cover coal (greater than 30 to 40 feet) only became commonplace in the 1960's with the proliferation of mining equipment capable of moving large amounts of rock efficiently. Early underground mining operations have left a considerable amount of abandoned underground

mines that are now candidates for remining. These underground mines have been producing untreated mine drainage since abandonment and, if left unchecked, will continue to do so for decades or even longer. Daylighting of abandoned underground mines is one of the more frequently employed BMPs during remining operations.

Daylighting operations are often economically marginal. This is because the same volume of overburden associated with virgin coal needs to be removed, but the coal recovery rates are greatly diminished. A coal recovery rate of 50 percent is usually the maximum observed at daylighting operations, but this level is seldom achieved. Recovery rates are more commonly in the range of 20 to 35 percent, because many of the mines were retreat mined (high coal extraction from partially mining through pillars as the operation withdraws from the mine) prior to abandonment. Because of this reduced recovery, the thickness of overburden that can be removed economically is less than that for solid coal areas.

The act of daylighting is the removal of the strata above the coal (overburden), the removal of the collapsed rock (gob) around the existing pillars, and the loading out of the coal. Once the coal is removed, the site is reclaimed. Daylighting works to reduce lateral ground-water infiltration in several ways. Abandoned underground mines are recharged, to a large degree, from fractures in the overlying rock. The fractures are created primarily by stress relief of erosional rock mass removal and to a lesser extent by tectonic (mountain building) activities (Wyrick and Borchers, 1981). One of the more prominent results of daylighting is that avenues for vertical recharge are eliminated, and water that once recharged the underground mine is no longer available.

Daylighting of approximately one half a 380 acre abandoned mine in Allegheny County, Pennsylvania reduced the flow by about 50 percent (Skousen and others, 1997).

Subsidence and collapse of abandoned mine workings can create additional fractures and increase the size of existing fractures, also increasing their transmissive properties. Evidence of subsidence is frequently observed at the surface as cracks, damage to surface structures (e.g., house foundations, roads, and utilities), and sinkholes (closed contour depressions).

Figure 1.2.1a is a photograph illustrating exposed fractures accentuated due to mine subsidence. The degree of surface disturbance depends to a large extent on the thickness and lithology of the overburden and the size of the mine void. Daylighting removes the highly transmissive avenues for ground water to enter underground mine workings. Even when the underground mine has not been completely eliminated, daylighting can dramatically reduce this recharge. Empirical observations indicate that there is an exponential decrease in recharge to underground mines with increasing overburden thickness. Shallow cover areas tend to yield more water to the mines than deeper (thicker) cover areas and are more commonly eliminated through remining. In shallow overburden, stress-relief fractures are more frequent and generally more transmissive than in deeper overburden (Borchers and Wyrick, 1981; Hawkins and others, 1996). Because of more extensive fracturing with shallow cover, the overlying rocks are more susceptible to the impacts from mine subsidence. For example, daylighting 20 percent of a mine, which is the shallowest cover, will likely reduce infiltration by an amount much greater than 20 percent.

Figure 1.2.1a: Example of Mine Subsidence and Exposed Fractures



The storage capacity of underground mines is considerable, and can approach 65 percent of the original coal volume. However, a storage capacity of 20-40 percent is more likely. A 100-acre

underground mine with 50 percent of the coal mined, a 5 foot thick coal seam, and no significant subsidence has a potential storage volume of over 81 million gallons. If the mine workings are only one third flooded, the mine water stored exceeds 27 million gallons. Storage of vast amounts of mine water in underground mines allows for continuous lateral recharge to adjacent operations, even during dry periods. Daylighting decreases the amount of storage available for ground water and therefore prevents lateral movement into adjacent areas.

Abandoned underground mines are commonly ideal environments for AMD formation. If acidic, metal-laden ground water is infiltrating into an adjacent surface remining operation, it can cause the formation of more AMD than the sum the two mines would produce separately. For example, it is known that ferric iron (Fe^{3+}), a product of acid-mine drainage formation, can become the main oxidant of pyrite. Additional pyrite oxidation can occur even under suboxic or anoxic conditions (Caruccio and Geidel, 1986). Therefore, AMD entering into pyritic-rich zones in spoil can produce more pollution than the spoil would produce on its own.

By and large, the water quality of underground mines is much poorer than that of surface mines on the same seams (Hawkins, 1995b). AMD formation is facilitated by the configuration of an underground mine which permits ground water to preferentially encounter commonly acid-forming units (seat and roof rock and the coal). Over time, roof falls and pillar deterioration continue to introduce additional acid-forming materials into the system. Daylighting is radically different than the mining processes that allow the underground mine to create AMD, because the coal mine entries are eliminated and the gob is mixed with the remainder of the overburden. The post-remining configuration of the daylighted sections becomes that of a reclaimed surface mine. However, because of roof falls and pillar deterioration, there may be a higher amount of unrecoverable coal mixed in with the spoil associated with daylighting than with remining surface mines. After daylighting, and in the absence of selective spoil handling, ground water flowing through the reclaimed portions will encounter acidic, alkaline, and/or relatively inert spoil materials at a frequency based on the volumetric content of the spoil and on the ground-water flow regime. With these changes to the ground-water flow and the materials contacted,

mine water is likely to be less acidic, especially with the presence of alkaline units in the overburden.

Daylighting of an abandoned underground mine on the Pittsburgh Coal seam in Allegheny County, Pennsylvania resulted in turning mine discharge water from “extremely acidic” to alkaline with low metal concentrations. The areas of the mine that were not daylighted continued to produce acidic mine water similar to the premining water quality (Skousen and others, 1997).

Daylighting of underground mines can reduce pollution loads through the reduction of ground-water infiltration and through changing the geochemical and physical properties of material that the ground water contacts. Daylighting eliminates potential recharge sources by mining out subsidence features. The original ground-water flow path is interrupted by the subsequent installation of seals and/or drainage systems. The potential amount of mine water storage is likewise reduced.

Before an underground mine is daylighted, the ground-water system exhibits primarily open conduit flow with water encountering seat rock, roof rock, and coal. All three of these units are typically pyritic, and thus possible acid generators. Once daylighting has occurred, the lithology and particle size of the overburden, whether alkaline, acidic, or inert, is greatly modified. This modification of the overburden strata substantially increases the amount of freshly-exposed rock surfaces that are accessible to the ground water. Following daylighting, the ground-water flow regime is a dual porosity system, where ground water is stored in large conduits and voids between spoil fragments, but exhibits overall intergranular flow characteristics through the finer-grained spoil (Hawkins, 1998a). With this change in the ground-water flow regime, the probability of ground water encountering alkaline or acidic material is proportional to the volume and surface area of that material in the spoil, whereas, prior to daylighting, the water almost exclusively contacted acid-forming materials. The intergranular flow through the fine-grained spoil exhibits the lowest transmissivity and is the controlling factor of the speed of ground-water flow in the backfill. Therefore, contact time with rock surface areas also is altered, and generally

lengthened by daylighting. These flow regime changes can have a significant impact on ground-water geochemistry.

Potential problems do exist with daylighting. Overburden material can be highly acidic, and disturbing it would allow for additional pyrite exposure and oxidation, release additional acidity, and possibly increase the pollution load. To prevent this scenario from occurring, potential acid-producing and alkaline-yielding zones, as well as the net acidity or alkalinity of the overburden, should be determined prior to remining. If the overburden is acidic, the anticipated reduction in flow that can result from daylighting may be offset by the additional acid production. In this case, alkaline addition or some other ameliorating BMP would be required. In addition, coal itself can be acidic (with total sulfur concentrations greater than 0.5 percent). The acidity potential of unrecoverable coal needs to be included in the acid-base accounting conducted for the site. Additional coal mixed in with the spoil and left in the backfill can be problematic for marginal sites.

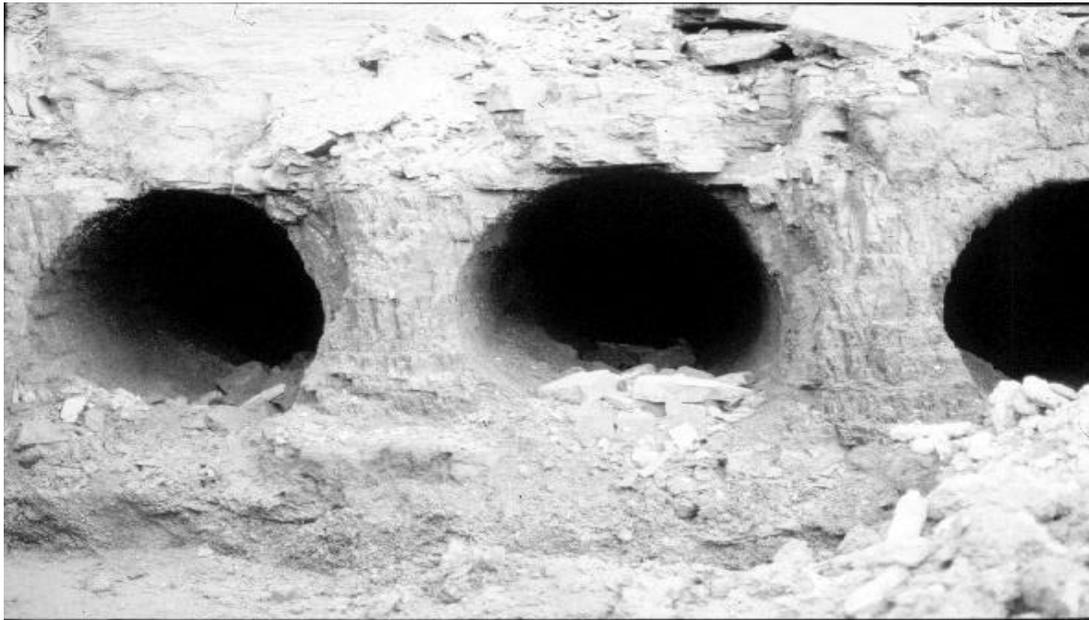
Another potential problem associated with daylighting is that underground mine workings have often collapsed and pillars have crushed, causing coal to spall off. Under these situations, separating coal from the waste rock can be difficult, and some of the coal will be unrecoverable. Industry estimates range between 5 and 20 percent of the coal may be left during daylighting.

Sealing and Rerouting of Mine Water from Abandoned Workings

As an integral part of daylighting, abandoned mine entries and auger holes exposed at the final highwall are sealed with a low-permeability material. Sealing these abandoned workings inhibits the infiltration of atmospheric oxygen. Sealing also prevents ground-water movement into these workings from the mine spoil and from these mine workings into the mine spoil. Figure 1.2.1b shows exposed auger holes that require sealing. The most common method of sealing an exposed mine entry or auger hole is by pushing, and compacting as much as possible, a low-permeability material into the abandoned workings with a bulldozer or other appropriate equipment. Compaction of the material is difficult to achieve because the inside of the seal is open ended.

When a material is pushed into the opening, there is nothing on the inside to push against to aid compaction.

Figure 1.2.1b: Exposed Auger Holes

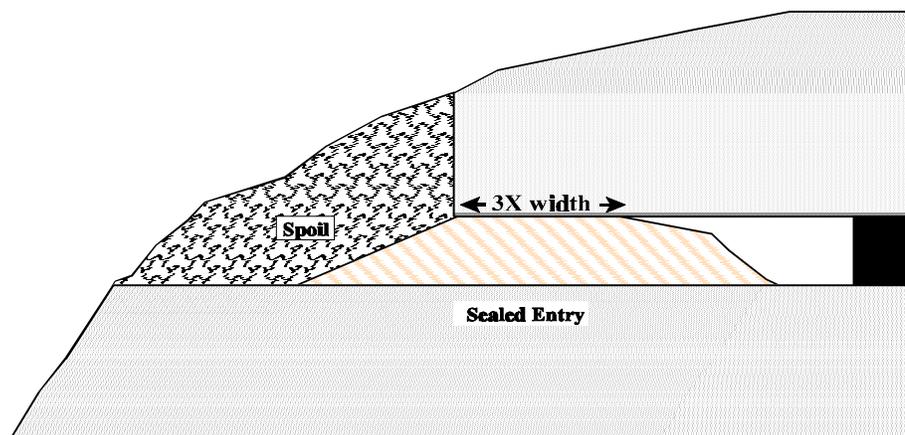


Achieving water-tight seals for auger holes and mine entries that have not been daylighted is extremely important. If these seals leak, a fluctuating water table may be created for the undaylighted portion of the underground mine. A fluctuating water table is possibly one of the worst conditions in an underground mine environment. When the water table drops, pyritic material is subaerially exposed, permitting oxidation. When the water table rises again, salts that were created by the pyrite oxidation, are hydrolyzed and mobilized, creating additional AMD. The importance of sealing these mine workings should not be taken for granted.

In some regions, constructed mine seals may be permitted. In Tennessee, a “brick wall” has been approved as a means of sealing exposed underground mine entries (Appendix A, EPA Remining Database, 1999). On a site-specific basis, other types of constructed water seals may be approved.

It is highly recommended, and in some states statutorily-mandated, to seal mine entries and auger holes to a depth equaling three times the widest dimension of the opening. For example, if the auger hole is 3 feet in diameter, the depth of the seal should be at least 9 feet. Figure 1.2.1c is a schematic illustration of a mine entry seal. Determining the depth of a seal is extremely difficult, if not impossible. It is doubtful that a mine entry that is 10 feet wide is sealed to a depth of 30 feet.

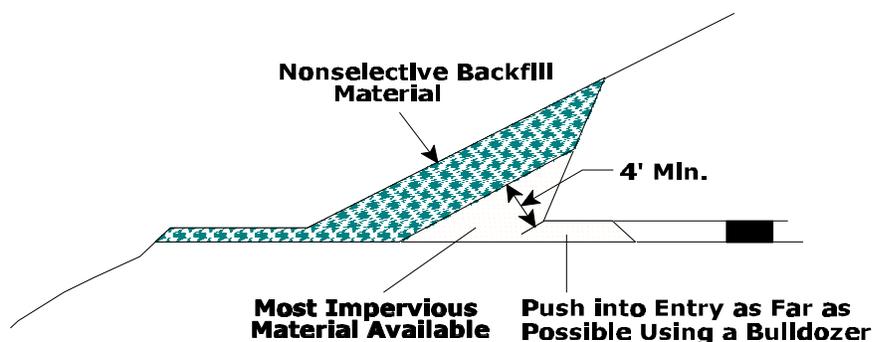
Figure 1.2.1c: Example of a Mine Entry Seal



Schematic Drawing of a Sealed Mine Entry

Not all states require that these mine workings be sealed to three times the widest dimension. Some require that the sealing material be pushed into the entry as far as possible with a bulldozer or other piece of equipment. Figure 1.2.1d illustrates this type of seal, as approved in Virginia.

Figure 1.2.1d: Example of a Virginia-Type Mine Entry Seal



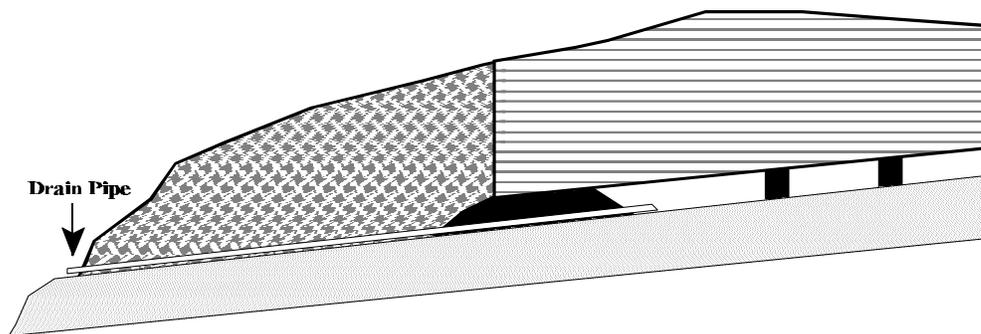
There are other problems with assessing the effectiveness of these seals. Daylighting abandoned workings often exposes numerous mine entries. Sealing of all exposed entries can require a large amount of material and is difficult to achieve because the inside of the seal is open ended. For example, if daylighting exposes 20 entries with average dimensions of 10 feet wide and 5 feet high, sealing will require over 1,100 cubic yards of material. This is a considerable amount of material to stockpile and handle, even if it is locally available. If not locally available, the material should be obtainable at a minimal cost.

The permeability of this material should be similar to that required for surface capping or stream lining material. The material should exhibit hydraulic conductivities of 10^{-10} to 10^{-9} m/s or lower to effectively inhibit ground-water movement. By comparison, coals in the northern Appalachian Plateau may have hydraulic conductivity values ranging from 10^{-6} to 10^{-5} m/s (Miller and

Thompson, 1974). If these mine workings are sealed properly with a low-permeability material, ground-water movement is more likely to be through the more permeable coal than through the entry seals.

Daylighting operations commonly encounter mine discharge points and/or water pathways during mining operations. The mine water will continue to flow through portions of the mine that have not been daylighted. Therefore, sealing of mine entries can cause extensive flooding of the remaining mine workings behind the seals. Under these hydrogeologic conditions, considerable hydrostatic head eventually will rest against these seals, causing a substantial amount of mine water to infiltrate into the backfill. This infiltration can occur even when seals are properly installed. These flooded areas can be dewatered by installation of a free-draining piping system to collect and transport the water through the entry seals and bypassing the backfill. The drain system prevents mine water from being exposed to the spoil. Figure 1.2.1e illustrates this potential-sealing scenario with the drain system in place. The system should be designed to accommodate the maximum flow anticipated.

Figure 1.2.1e: Example of a Mine Drain System

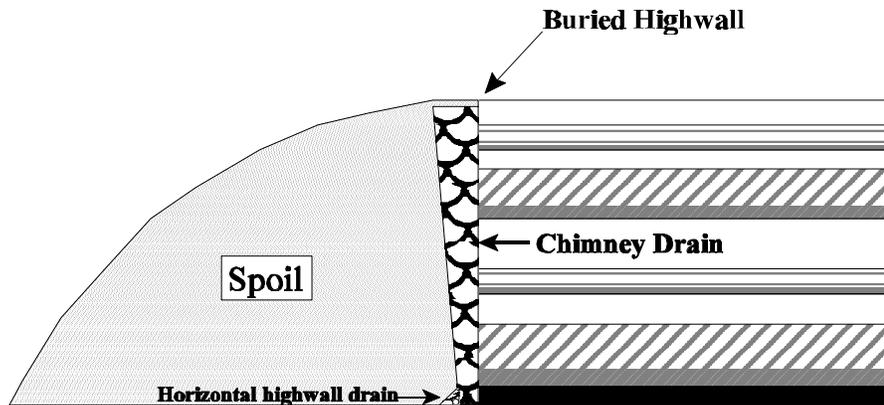


Highwall Drains

There are two basic forms of highwall drains (horizontal and vertical) that work together or separately to collect ground water entering the spoil from the highwall. Horizontal drains can be installed to work on a stand alone basis. Vertical (chimney) drains usually are not installed as stand alone, but are commonly tied into a horizontal drain. Highwall drain systems work to minimize or prevent the contact between ground water and potentially acid-forming spoil by interception, collection, and transport away from the spoil. If the water quality is within compliance standards, the water can be discharged directly. If not, it will require treatment prior to release.

Highwall-drain systems can also function to collect surface water prior to infiltration at the interface between the highwall and spoil. This horizontal-pipe system is installed with a perforated pipe running along the surface or just below the surface, parallel to the highwall. The surface pipe is connected to a solid pipe that runs from the surface to the pit floor, where it is tied into a horizontal highwall drain (Gardner, 1998).

Chimney drains are highly-transmissive linear zones of rock installed vertically at the highwall. Chimney drains collect ground water as it enters spoil from the highwall and channel it downward toward the pit floor (Figure 1.2.1f). These drains are usually installed at a known inflow point (observed during mining), such as a ground water-bearing fracture or fracture zone exposed at the final highwall. Chimney drains are usually tied into a horizontal drain installed at the base of the highwall in order to channel the water away from the bulk of the backfill. Water captured by a chimney drain is channeled to an integral horizontal drain located at the base of the highwall. This water is then drained laterally and is subsequently discharged away from the spoil. In some cases, a highwall drain also be constructed of perforated pipe buried vertically at the highwall. If a pipe drain is used, it should be surrounded by coarse rock to facilitate drainage.

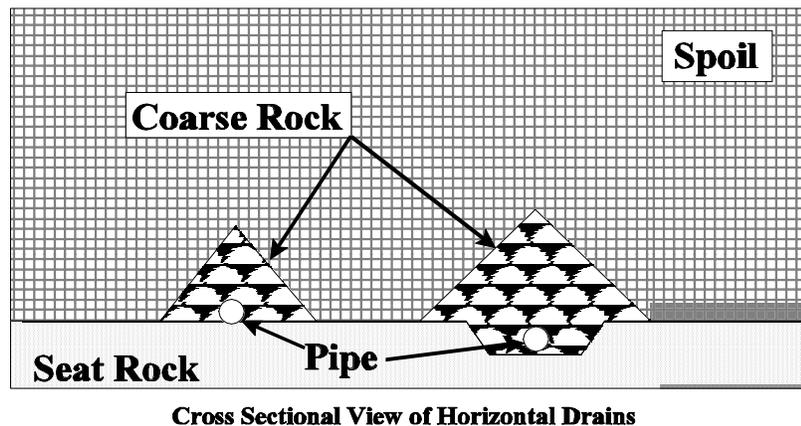
Figure 1.2.1f: Cross Section of an Example Chimney Drain

For chimney drains to work effectively, they need to be substantially more transmissive than that anticipated for the spoil. A median hydraulic conductivity of 1.7×10^{-5} m/s was determined from aquifer testing of 124 wells in mine spoil from 18 mines tested in the northern Appalachian Plateau (Hawkins, 1998a). Drains should have a hydraulic conductivity two orders of magnitude (100 times) higher than this value. The need for this difference in hydraulic conductivity is based on the difference in the definitions of an aquifer and an aquitard. With a hydraulic conductivity difference of two orders of magnitude, ground water tends to move through the aquifer and not through the adjacent aquitard. The relatively-high hydraulic conductivity required for the drain necessitates that the material is a uniform coarse-sized durable rock. Rock size can vary, but should be large enough to ensure long term drain integrity and preclude piping of the drain material. Drains comprised of rock one inch or larger have been successful. Inert, well-indurated (cemented) sandstone or a limestone is frequently employed to ensure the desired life span.

Horizontal drains are commonly installed at or near the base of the final highwall to collect ground water entering from undisturbed strata or adjacent unrelated surface mine areas. Ground and surface water often infiltrate into mine spoil at the highwall. If this water is not collected by a chimney drain, it tends to migrate downward taking a path close to the highwall toward the pit floor. Horizontal highwall drains are installed to intercept this water and remove it from the site before the water encounters additional spoil. If present, chimney drains are tied into the horizontal drain.

Horizontal drains are either constructed directly on top of the pit floor or are incised a few feet into the seat rock. The latter appears to be a more efficient method for collecting water. Figure 1.2.1g illustrates two common types of horizontal highwall-drain construction. These drains consist of a perforated pipe placed into a core of coarse-grained rock. Rock composition and size should be similar to that used for chimney drains. Pipe diameter should be large enough to easily transmit more water than the predicted highest flow. Four or six inch diameter, flexible perforated plastic pipes are the more common pipes used for horizontal drain construction. At sites where extreme flows are anticipated, a larger pipe diameter may be necessary.

Figure 1.2.1g: Cross Section of Horizontal Highwall Drains



Drain orientation depends to some degree on the structural dip of the pit floor. Horizontal highwall drains, as with pit floor drains (discussed in a later section), need to have sufficient grade to properly drain water from the spoil. Once ground water enters the drain, it should flow rapidly through the pipe and be discharged away from the site. These drains are designed to prevent the formation of a defined ground-water table. If the drain system is ineffective, a water table will form and some of the ground water will bypass the drain, continue to flow through the spoil, and eventually discharge as mine drainage at some point down gradient at or near the toe of the spoil. The drain outflow point should have an air trap installed to prevent atmospheric oxygen from migrating back into the backfill and possibly oxidizing additional pyrite.

An important factor in the implementation of highwall drains is the collection and transportation offsite of as much water as possible, before it encounters the spoil. A clear understanding of the surface water drainage system and the ground water-bearing zones or fractures is imperative. A good idea of from where the water will be infiltrating is required to design and install an efficient highwall drain system. However, some spoils are so highly conductive, a properly installed drain will collect the water shortly after it enters the spoil, regardless of infiltration points or zones. Care should be taken to ensure that the drains have sufficient grade to efficiently drain water away from the spoil and discharge it freely.

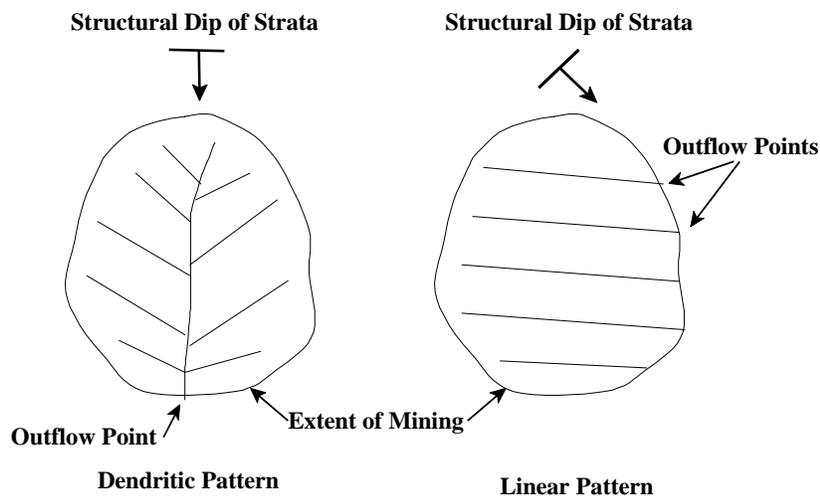
Pit Floor Drains

Pit-floor drains are similar in construction to and perform a similar function as horizontal highwall drains. Depending on the dip of the pit floor, they can be tied into each other to create a common drainage system. Pit-floor drains are designed to capture ground water that has entered the backfill either through lateral or vertical infiltration. The water is then rapidly drained from the site without intercepting additional spoil material.

Pit floor drainage patterns should be designed so that the majority of the ground water in the backfill is collected and the ground-water table is greatly suppressed, if not eliminated. Construction of pit floor drains is similar to construction of highwall drains, but the orientation and layout design are substantially different. Figure 1.2.1h illustrates the cross-sectional view of

two common methods for constructing pit floor drains, and two of the more common pit floor drainage patterns. Efficient pit floor drainage is not exclusive to these two patterns. There are a multitude of drain plan view layout designs that should work effectively to collect ground water. The drainage pattern employed should be site specific.

Figure 1.2.1h: Pit Floor Drain Patterns



The dendritic pattern is similar to stream drainage patterns. There is a main stem with a series of tributaries that intersect it at angles less than 90 degrees. This drainage pattern contains one common outflow. Drain tributaries need to be positioned with respect to the dip of the pit floor to allow water to drain freely. Tributaries also need to be at an oblique angle to the dip so they will intercept as much ground water as possible, yet still drain properly. Air traps should be placed at the outflow point to prevent atmospheric oxygen from migrating freely back into the spoil.

The linear pattern is composed of a series of evenly-spaced parallel drains with each drainpipe having a discrete outflow point. These drains, like those of the dendritic pattern, need to be at an

oblique angle to the dip, where a substantial amount of the ground water is intercepted, while maintaining sufficient grade to allow free drainage off of the site. Air traps should be placed at the outflow points to prevent atmospheric oxygen migrating freely back into the spoil.

Determination of the probable transmissive properties of spoil and the appropriate spacing of drains is critical to the effectiveness of this BMP. Parallel pit floor drains installed on a site in Westmoreland County, Pennsylvania, were spaced at roughly 500 to 600 foot intervals. Figure 1.2.1i shows the construction of a pit-floor drain at this site. Preliminary monitoring results indicated that this spacing may be too broad. Monitoring wells indicated the presence of a defined water table in parts of the backfill, and water levels in the monitoring wells were typically 3 to 5 feet above the pit floor. The drains installed were not completely suppressing the ground-water levels, but were keeping them lower than expected for nondrained spoil. The spoil at this site is comprised almost entirely of shales, which caused the backfill to be less transmissive than originally anticipated. Sandstone-rich spoils are expected to be more transmissive, requiring a wider drain spacing than shale-rich spoils. In this case, the drain spacing was inadequate for the given site conditions. Future operations should be specifically engineered to account for the expected spoil hydraulic properties.

Figure 1.2.1i: Example of a Pit Floor Drain



The engineering and construction of pit-floor drains are critical to their efficient use. These drains should be installed so they intercept the ground water flowing across the pit floor, with sufficient grade to drain water freely. Too broad a spacing between drains with regard to the spoil hydraulic conductivity and expected heterogeneity will permit the formation of a water table between the drains. Drain spacing and configuration should be based on a forecast of the spoil hydraulic conductivity and heterogeneity based on overburden lithology, mining equipment employed, direction of mining, and direct aquifer testing on nearby reclaimed surface mines.

There is a caveat with incising drains in to the pit floor. Excavation into a pit floor can breach the integrity of the seat rock and facilitate infiltration of mine water into underlying aquifers. Once ground water infiltrates into underlying units, it is less controllable and can eventually discharge at a point far removed from the site.

Grout Curtains

Grout curtains are vertical or nearly vertical, tabular-shaped, low-permeability layers that are emplaced to prevent or divert ground-water movement. In remining operations, grout curtains can be installed at and against the highwall or they can be installed in the undisturbed strata above the highwall. A limiting factor for the installation of grout curtains in remining situations is that they tend to be more expensive than some of the alternative BMPs. It is doubtful that grout curtains will be used often as a BMP, because the narrow profit margin in most remining operations.

Grout curtains or barriers can be installed during reclamation by pushing and compacting a low permeability material (grout, clay, coal combustion waste, and other materials) against the highwall as reclamation progresses.

This is conducted in lifts with each lift tied into the previous one. Grout curtain material is typically either an on-site material (clay) or an inexpensive waste material, such as CCW. Clays commonly have hydraulic conductivities ranging between 10^{-12} to 10^{-8} m/s (Freeze and Cherry, 1979). Yanful and others (1994) recorded an initial hydraulic conductivity of 10^{-9} m/s for

compacted clay used to cap an acid-producing waste rock site. The importance of compaction of the barrier material in the creation of a low-permeability barrier should not be overlooked. A continuous barrier is needed to effectively prevent ground-water movement. Any breach in this barrier can permit ground-water movement from the strata into the spoil.

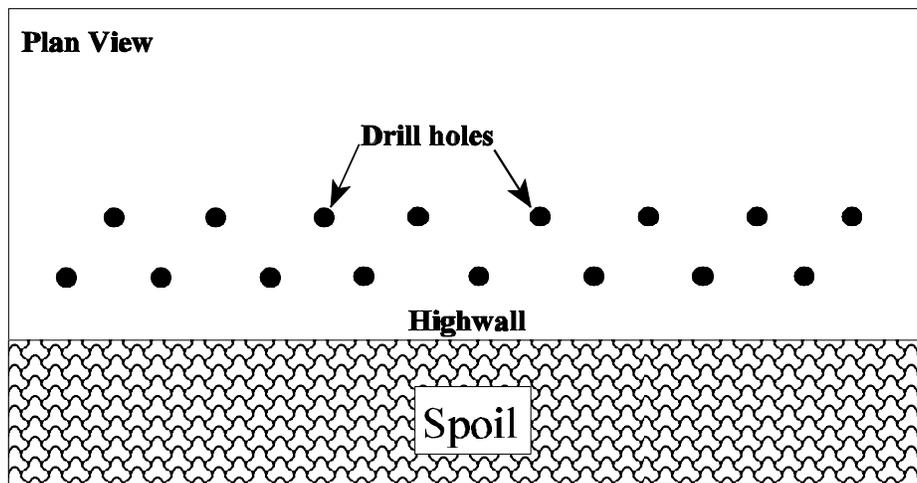
The “haulback” of CCW to a mining operation is often a provision of the sale of coal to electrical generating facilities. With the addition of water, CCW is often pozzolanic (self cementing). The permeability of this material, once hardened, is sufficiently low to nearly preclude all ground-water flow. The Electric Power Research Institute (EPRI) reported a range of hydraulic conductivities for “self-hardening ashes” of 3.2×10^{-9} to 1.8×10^{-7} m/s (EPRI, 1981). These values were determined after a 28 day set-up period. Hellier (1998) reported a hydraulic conductivity of 10^{-9} m/s for a fluidized bed combustion ash used for a surface mine capping project in north central Pennsylvania.

At some mining locations, the installation of a grout curtain at the highwall after reclamation has been completed. In these cases, the spoil directly adjacent to the highwall has to be re-excavated and a slurry-type grout used to fill the trench. Though grout types can vary considerably, grouts containing high percentages of CCWs and cement or bentonite and cement are frequent choices. Potential problems can arise from highly-permeable spoil. If the grout is watery and flows too freely, it will enter the spoil and construction of a continuous, effective barrier is difficult. This after-the-fact grout curtain would be expensive and probably cost prohibitive for remining operations.

Grout curtains also can be installed above the highwall in undisturbed strata by performing a pressure grouting operation. A series of boreholes are drilled across the site parallel to the highwall. These holes are often drilled in a staggered pattern to maximize the grouting potential by accessing as many natural fractures as possible (Figure 1.2.1j). Spacing of boreholes varies depending on fracture density and transmissivity and on the propagation characteristics of the grout. Grout holes drilled on ten foot centers have been suggested for sealing underground mines (U.S. Environmental Research Service, 1998). Given the common orientation and density of

stress-relief fractures in the Appalachian Plateau, drilling grouting holes at a slight angle (up to 3 degrees) from vertical will help to optimize efficiency. A commonly-used pressure grouting material is a commercially available polyurethane. The polyurethane is a two component material that is injected simultaneously in equal amounts (Ackman and others, 1989). Other materials suitable to this type of grouting, are neat cement or bentonite.

Figure 1.2.1j: Common Drilling Pattern for Pressure Grouting Wells



Problems with the implementation of grout curtains are often related to the continuity of the emplaced grout. Ground water is expected to impound behind a grout curtain and eventually flow laterally away from the spoil. If the grout curtain is not continuous, ground water eventually will flow through a breach, following the path of least resistance. Pressure grouting in fractured rock aquifers is particularly problematic, because the fractures are not continuous, are not all interconnected, and do not necessarily interact with one another. It has been observed that individual fractures may represent discrete aquifer zones and may have distinctly different piezometric surfaces (Booth, 1988). Rasmuson and Neretnieks (1986) estimated that only 5 to

20 percent of the fracture plane transmits 90 percent of the water. A study of overburden material at a surface mine in Clearfield County, Pennsylvania, illustrated that only a few discrete fractures intercepted by a borehole actually contributed to the well yield. The remainder of the fractures appeared to be unconnected or poorly connected to these active fractures (Hawkins and others, 1996). Grout hole spacing, grouting material, and grouting pressures need to be designed to overcome these potential fracture discontinuity problems. It is recommended that grouting wells be drilled at a slight angle from true vertical to increase the likelihood of encountering vertical or near vertical water-bearing fractures.

Ground-Water Diversion (Interceptor) Wells

Diversion wells are installed specifically to intercept and collect ground water prior to its infiltrating into the reclaimed backfill. These wells are drilled up gradient of the backfill area and can be oriented vertically or horizontally. Care should be taken not to over pump these wells, which can cause a reversal of ground-water flow. If the water table is lowered to the point that ground water is drawn from the reclaimed operation, the water may require treatment prior to discharging. The intent of diversion wells is to prevent water movement into the strip, not to create a pump-and-treat operation.

Vertical diversion wells require a pumping system operated by a consistent power supply. In order for vertical diversion wells to effectively intercept ground water, a series of wells drilled normal (perpendicular) to the structural dip and up gradient are required. Spacing of these wells depends on site-specific conditions, such as fracture density, hydraulic conductivity, and structure. Well depth is generally to or a short distance below the top of the seat rock. In relatively shallow wells (less than 200 feet) of the Appalachian Plateau, the highest well production occurs at the shallowest depths (Hawkins and others, 1996). However, there are circumstances where substantial ground water flows in from deeper fractures. In competent rocks in the Appalachian Plateau, the entire borehole should be left open to prevent restriction of any ground-water inflow points. As with grouting boreholes, these wells may be more efficient if they are drilled at a slight angle (1 to 3 degrees) to increase the probability of intercepting vertical fractures.

Diversion wells should be configured so that pumping will initiate when the water reaches a pre-defined level above the bottom of the coal and that pumping will cease once the water is drawn down to second pre-defined level, commonly at or near the base of the coal. Pump cycling times depend on the amount of ground water present, transmissivity of the strata, and the efficiency of the well. Diversion wells are relatively inexpensive to drill, but can be expensive to complete and maintain over a period of time. Therefore, they will seldom be an economically viable option for remining.

Horizontal diversion wells, when properly installed, may be more efficient and effective than a series of vertical wells, depending on the size of the area to be dewatered.

The initial cost of a horizontal well will be dramatically more than the equivalent footage of vertical wells. However, there are definite advantages to horizontal wells. They can be drilled to allow for free drainage. No pumping system or power is required with a free-drainage system, and thus, very little maintenance is required. Horizontal wells access water from a continuous horizontal line, rather than from discrete well points, and are more likely to intersect water-bearing fractures. Because of the high cost of outfitting and maintaining the pumping systems of vertical well sets and the initial high cost of drilling horizontal wells, it is doubtful that diversion wells will be an economically viable option at more than a few remining operations.

The installation of diversion wells encounters some of the same poor fracture interconnection problems as are incurred during the installation of grout curtains. Because individual fractures can represent discrete piezometric zones (Booth, 1988), diversion wells need to be drilled in a configuration and at a spacing that accesses all of the discrete ground-water flow systems. A common occurrence in the Appalachian Plateau is for shallow water wells (less than 200 feet) a short distance apart (less than 100 feet) to show little interconnection based on an aquifer test. Drawdown at a pumping well may exceed 100 feet while a well 50 to 80 feet away may only exhibit a drawdown of a fraction of an inch over the length of a pumping test lasting 2 hours or more. It is advised to drill the vertical diversion wells at a slight angle from true vertical to increase the likelihood of encountering vertical or near vertical water-bearing fractures. It is also

recommended to drill horizontal diversion wells at an angle to the preferred orientation of the vertical stress-relief fractures. Because vertical fractures are created by tensional forces and tend to be oriented parallel to the strike of the adjacent valley (Borchers and Wyrick, 1981), horizontal diversion wells should be drilled at an angle that is subparallel to the valley orientation.

Design Criteria

These BMPs should be designed and implemented to preclude the lateral infiltration of ground water into the backfill areas of reclaimed remining operations. Some of the salient design criteria for each of the BMPs discussed in this chapter are included in the list below. Site-specific conditions will ultimately dictate which BMPs should be used and the scope of BMP implementation required in order to reduce or eliminate lateral ground-water inflow, discharge rate and pollution load. It should be noted that although grout curtains can be employed as a BMP, they are rarely used and the technology is unproven.

Daylighting

- Eliminate subsidence-induced ground-water infiltration zones.
- Eliminate vast ground-water storage areas.
- Reduce the amount of ground-water contact with acid-forming materials.
- Increase the possibility of ground water contacting alkaline materials.
- Facilitates special handling of acid-forming materials.
- Greatly reduce the oxygen flow to the subsurface.

Sealing and Ground Water Rerouting of Mine Workings

- Inhibit atmospheric oxygen infiltration into mine workings.
- Use low permeability sealing material (e.g., equal to or less than 10^{-9} m/s).
- Install seals to preclude ground-water movement into or out of the mine workings.
- Drain to control the ground-water buildup, bypass the spoil, and discharge off site.

Highwall Drains

- Intercept and collect ground-water infiltration at the highwall.
- Quickly drain ground water from the spoil and discharge it off-site.
- Make drains more permeable than the surrounding spoil.

Pit Floor Drains

- Orient and construct the drains to collect ground water within the backfill.
- Suppress or eliminate the ground-water table within the backfill.
- Orient and construct the drains to quickly drain ground water from the spoil and discharge it off site.

Grout Curtains

- Install to prevent or redirect ground water away from the backfill.
- Use low-permeability grouting material (e.g., equal to or less than 10^{-9} m/s).
- Ensure that continuity is maintained across the potential infiltration zone.
- Drill grout holes at an angle of up to 3 degrees (depending on site strata) to increase the interception of vertical fractures.

Diversion Wells

- Locate and drill up-gradient of the mine to intercept ground-water flow.
- Make intersection of water-bearing fractures or zones a priority.
- Use low or no-maintenance systems, if possible.
- Install horizontal wells at an angle subparallel to valley orientation.

1.2.2 Verification of Success or Failure

The cumulative discharge rate of the post-reclamation discharges compared to pre-mining discharges is, as with all of the physical hydrogeologic BMPs, the truest indication of the effectiveness of ground-water control BMPs.

Daylighting

Verification of the amount of daylighting that has occurred is relatively easy. The acreage disturbed can be viewed during mining and after reclamation and compared to underground mine maps. If there is uncertainty of the exact amount of daylighting that occurred, the area can be surveyed.

Sealing

Verification of the implementation of sealing of abandoned mine workings will require the inspection staff to be present during different phases of the operation. Once seals are in place, they will be covered. If there is concern that the mine workings will not be properly sealed, the permit may be conditioned to require notification when sealing will occur or will be completed. The material to be employed to seal the openings may need to be stockpiled on site to confirm the type of material and the amount to be used. The stockpile should be marked to distinguish it from spoil or topsoil piles. To be sure the material has a sufficiently low permeability, the relative hydraulic conductivity also may need to be certified by laboratory testing. As previously stated, it is extremely difficult to verify the depth to which the seal is emplaced. If this parameter is deemed important enough, boreholes can be drilled behind the seal and a borehole video camera can be lowered to view the seal from the inside and/or to monitor the flooding of the remaining mine voids. It is doubtful that this step will be necessary.

Drains

If drains are installed in conjunction with the seals, drain piping can be viewed as it is installed. Drain outflow can be monitored to determine if it is yielding the anticipated volume of mine water. That is, does the drain yield a similar volume before and after mining. A mine consistently yielding 300 gpm prior to mining and drain installation and a median flow of 85 gpm after reclamation would indicate that the seals and/or the drain are not functioning properly. The existence of toe-of-spoil seeps may also indicate that the drains are working improperly.

Pit floor drains are installed as mining progresses, and tend to be extended with each phase (cut) of the mining operation. Pit floor drains can usually be inspected during several phases of the

operation. Effectiveness of these drains can be determined once the backfilling is complete. If the drains are yielding water and unexpected discharge points (seeps) are nonexistent, it is an indication that the drains are effectively collecting ground water. Monitoring wells installed in the backfill provide the best indication that the water table is being suppressed as designed. Site monitoring should be continued for a period beyond the anticipated water table re-establishment, and monitoring through several wet seasons is important. In the Appalachian Plateau, the backfill water table can require at least two years to completely re-establish.

Grout Curtains

The type of grout curtain installation monitoring depends on the method used to install the grout curtain. If the curtain is created as the site is backfilled, an inspection staff can review portions (lifts) of the installation as it progresses.

In situations where the installation of a grout or clay curtain along a significant portion of a highwall takes a protracted period of time and the inspection staff cannot be present for every stage implementation, estimates of the amount of material required should be submitted as part of the reclamation plan. Marked stockpiles or weigh slips equaling the proposed volume can be used to determine if the proper amount of material was used.

Determination of the success of grout curtains emplaced via pressure grouting drill holes is substantially more difficult. Grouting effectiveness can be evaluated indirectly by comparing the estimated porosity of the strata, the total volume of the strata, and the volume of grout employed. The ultimate effectiveness of grout curtains, regardless of how they were installed, is whether they preclude ground-water movement through them. To make this determination, monitoring wells can be installed on each side of the grout curtain.

Diversion Wells

There is little that can be viewed at the surface during the installation and use of diversion wells to ascertain their efficacy.

The effectiveness of diversion wells can be estimated by the amounts of water pumped from them and monitored by the construction of monitoring wells both up and down gradient of the pumping wells. If the down-gradient wells exhibit a suppressed ground-water table over the anticipated levels, it is indicative that the diversion wells may be functioning properly. Ultimately, if discharge rates are reduced, the diversion wells are effective.

Implementation Checklist

Monitoring a site for anticipated changes is a critical and inherent aspect of BMP implementation and efficiency determination.

Monitoring should continue well beyond initial water table re-establishment period (e.g., about 2 years after backfilling). The list below is a recommended guideline for an inspection staff to monitor and evaluate ground-water control BMPs.

- Measurement of flow and sampling for contaminant concentrations at time-consistent intervals.
- Assessment of hydrologically-connected units, as well as individual discharges, for pollution load changes.
- Review or inspection of sealing material weigh slips, receipts, or marked stockpiles.
- Review of implementation initiation and completion dates
- Assessment of any deviation from an approved implementation plan.
- Inspection of salient phases of the BMP implementation for:
 - a. integrity of seals.
 - b. drain construction, location, and orientation.
 - c. grout curtain integrity and continuity.
 - d. diversion well locations and productivity (yield).

1.2.3 Case Studies

Case Study 1 (Appendix A, EPA Remining Database, 1999 PA(3))

Remining was performed on an abandoned surface mine and abandoned underground mines in the Pittsburgh coal seam. A total of 33.8 acres (48 percent) of the 69.6 acres of abandoned surface mine land within the permit boundary were reclaimed by the operation. Of the 90 acres of abandoned underground mines in the Pittsburgh coal seam, at least 49 acres (54 percent) were daylighted during the remining operation. More than 203 acres were impacted by the remining operation. Fourteen pre-existing mine drainage discharge points were included in the permit. BMPs listed in the permit included regrading of abandoned mine spoil and highwalls, underground mine daylighting, sealing of exposed mine entries, special handling of toxic materials, and revegetation. The most predominant BMP components were regrading/revegetation and daylighting. The site was completed in June of 1998. Ten discharge points were used to determine the impacts of remining. The remaining four discharges were low flow and discharged intermittently during pre- and post-mining periods.

Because this site has been reclaimed relatively recently and post-remining data are limited, the resulting pollution load analysis is less than ideal and subject to change. However, this site is worth evaluation because of the large percentage of daylighting that was implemented and because it drains to a stream that is used as a public water supply. Additionally, considerable discharge reductions were observed prior to final backfilling for several of the monitoring points.

Two of the main discharges (MP-1 and MP-4) began to exhibit significant flow reduction prior to the completion of reclamation. Prior to October, 1992, MP-1 ranged in flow from 0 to 139 gpm with a median of 18 gpm. Since October of 1992, MP-1 ceased to flow, except for one monthly sample where the flow rate was 0.25 gpm. The flow rate of MP-4 ranged from 0 to 132 gpm with a median of 6.9 gpm prior to April of 1994. After that time, the flow ranged from 0 to 18 gpm with a median of 0.1 gpm. Figures 1.2.3a and 1.2.3b illustrate the flow reduction exhibited by these two discharges over time.

Figure 1.2.3a: Change in Flow Over Time (Case Study Discharge MP-1)

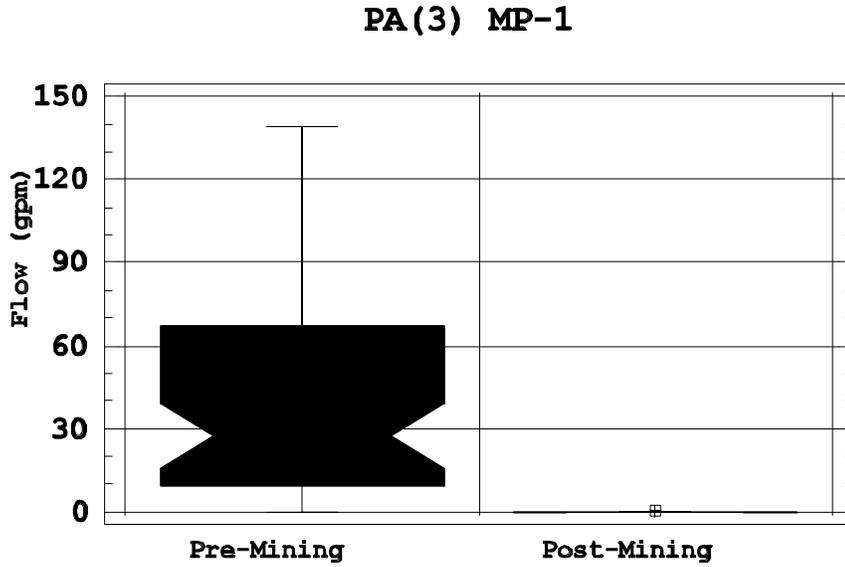
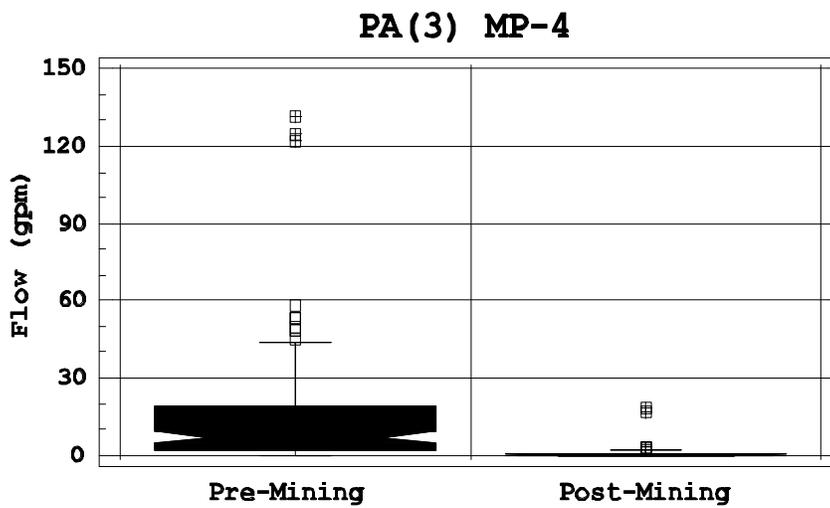
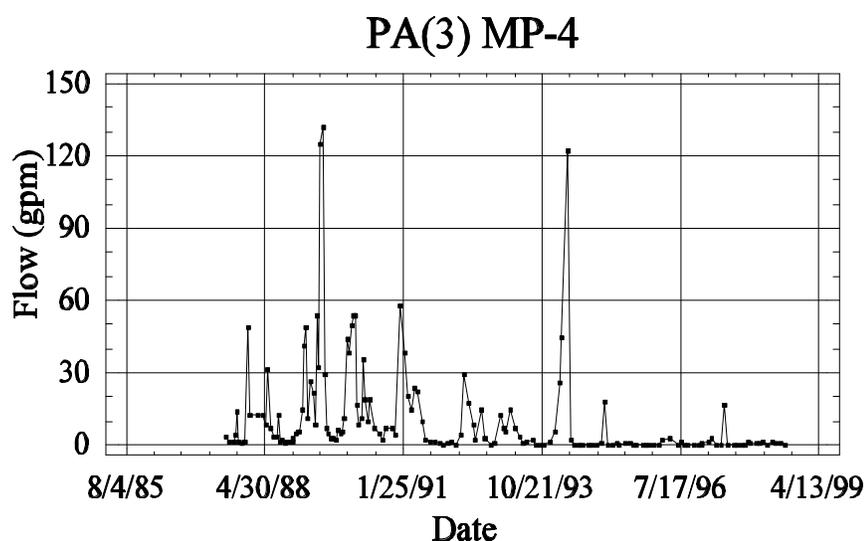


Figure 1.2.3b: Change in Flow Over Time (Case Study Discharge MP-4)



These analyses indicate that a flow reduction was observed even prior to complete backfilling (Figure 1.2.3c). MP-1 and MP-4 are directly down gradient from the first areas to be mined and reclaimed, and down gradient of limited-sized recharge areas. Therefore, it should be expected that these points would exhibit the greatest change during remining operations.

Figure 1.2.3c: Flow Rate Reduction, Pre- and Post-Remining Periods (Case Study Discharge MP-4)

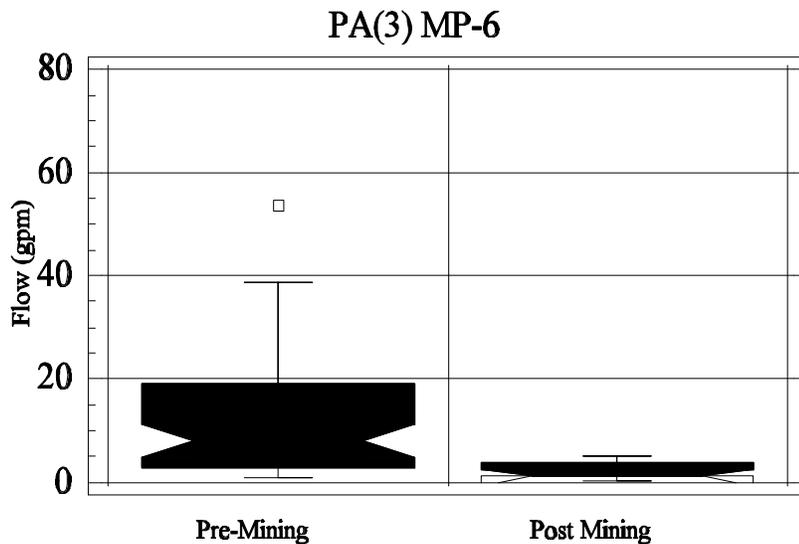


Pre- and post-remining comparisons (discharge points MP-2, MP-3, MP-5, MP-6, and MP-D) exhibited no apparent change in flow. However, flows for MP-A and MP-B appear to have decreased slightly, although not significantly. Although MP-C shows a slight, but significant, increase in median flow (from 0.5 to 2.9 gpm) from before to after November of 1994, the actual change in flow is relatively low by comparison to flow rate for most of other discharges.

Analysis of the post-mining data is, at this stage, preliminary. Only data for the first two months after remining were submitted for four of the discharges (MP-4, MP-5, MP-C, and MP-D) and these discharges have been excluded from the evaluation of pre- versus post-mining water

quality. Four of the remaining discharges (MP-1, MP-6, MP-A, and MP-B) exhibited a post-remining median significantly below the background data at a 95 percent confidence interval. This improvement in water quality is illustrated in Figure 1.2.3d. Three of the discharges (MP-1, MP-A, and MP-B) have been nearly or completely eliminated. The two remaining discharges (MP-2 and MP-3) exhibited a median flow rate reduction that was not statistically significant.

Figure 1.2.3d: Flow Rate Reduction, Pre- and Post-Remining Periods (Case Study Discharge MP-6)



The results discussed above should be tempered with the knowledge that precipitation for the 32 month baseline period was near average (i.e., a mean of +0.05 inches per month), while the brief post-remining period (6 months) was significantly below the average (i.e. a mean of -0.50 inches per month). Post remining monitoring should be continued until the precipitation has returned to near average for several months (preferably 6 to 12 months) and the water table has been fully re-established. Precipitation data were compiled from the Pittsburgh International Airport, approximately 37 miles west of this mine site.

Case Study 2 (Appendix A, EPA Remining Database, 1999, VA(7))

This site is located in Wise County, Virginia. The coal seams being remined are the Imboden Marker, Lower Kelly, Upper Kelly, Kelly rider, Lower Standiford, Upper Standiford, Taggard Marker, Bottom Taggard, Top Taggard, Owl, and Cedar Grove.

The permitted acreage is 1,140, with 149 acres to be regraded, 158 to be reclaimed, and a total of 498 acres to be disturbed. Daylighting will occur on previous augering of the Standiford seams. Abandoned mine workings will be daylighted on the Upper Standiford. It is also probable the abandoned mine workings on the Upper and Lower Kelly seams will be intersected and partially daylighted.

There are three discharge points (SB-5, SB-6, and SB-7) that were identified as pre-existing mine discharges. Although this site was still active as of January 1999, it is worth evaluating because it illustrates the type of remining occurring in Virginia and a substantial amount of daylighting and sealing of abandoned mines and auger holes is being performed.

Preliminary analysis of flow data yielded mixed results, but indicates an overall flow decrease. A comparison of baseline flow rates to flow rate during mining indicates that two of the three discharges (SB-6 and SB-7) have a reduced median flow.

The reduced flow was significant at a 95 percent confidence level for SB-7. SB-5 exhibited an insignificant increase in median flow for the same time periods. The sum of the median flows for baseline was 97 gpm compared to a median 53.5 gpm during remining, yielding a possible flow reduction of 45 percent. Evaluation of these results should acknowledge that climatic (e.g., precipitation) conditions were not considered during the analysis. Long term post-remining monitoring with determinations of precipitation during the same period, as well as that for the background period will yield a true assessment of the impact of remining on the pollution load.

1.2.4 Discussion

The BMPs discussed in this chapter, when properly employed under the right conditions, will successfully reduce the lateral infiltration of ground water into the backfill and should subsequently reduce the discharge rates. However, these BMPs cannot be viewed as a panacea for all of the pre-existing problems at a site. There are limits to what can be physically achieved and/or economically attempted. The two lists below (Benefits and Limitations) include, but are not limited to, what should and should not be expected of these BMPs.

Benefits

- Reduce pollution loading from abandoned mine land.
- Establish an alternate, improved hydrologic balance at the site.
- Eliminate surface subsidence features (e.g., sinkholes, disappearing streams, etc.).
- Highwall drains can be installed at the observed infiltration points.
- Control of the location of post-mining discharge points in case treatment is required.
- Daylighting often results in little profit, however, it is implemented as an integral part of the mining operation.
- Special handling of acid-forming materials.
- Reduction of oxygen flow to the subsurface.

Limitations

- Current implementation of these BMPs lacks comprehensive evaluation of effectiveness for pollution prevention.
- Previous use of some of these BMPs (pit floor and highwall drains, highwall sealing, and diversion wells) has been limited, therefore the true extent of their effectiveness has not been adequately determined.
- The true effectiveness of mine seals, drains, and grout curtains installation cannot be determined prior to reclamation and establishment of the post-mining hydrologic regime.
- Given the highly heterogeneous and anisotropic nature of surface mine spoil, the present state of predictability of the post-mining ground-water flow system is limited. It is

doubtful that an extremely high degree of predictability of the efficiency of highwall and pit floor drains is possible.

- Complete exclusion of laterally-infiltrating ground waters is not likely, therefore there needs to be a realization that the discharges will likely not be entirely eliminated.
- Diversion wells are costly and even the best planning may not provide an effective BMP system, if the hydrologic system is poorly understood.
- Success of daylighting can be dependant on the geochemistry of overburden material and special handling of acid-forming materials.

Efficiency

Analysis of completed remining sites in Pennsylvania (Section 6, BMP Efficiencies) indicated that at least 90 percent of discharges impacted by ground-water control BMPs will either exhibit a significant improvement, no change in the pollution load, or be completely eliminated (in the case of manganese, 89.5% of the affected discharges were improved, eliminated or unchanged).

For a total of 164 discharges with elevated acidity levels from remining operations in the state of Pennsylvania (Appendix B, PA Remining Site Study), slightly over 43 percent were improved or eliminated, over 56 percent were unchanged, and less than one percent were significantly worse from daylighting.

Of the 156 discharges with elevated iron, nearly 40 percent were improved or eliminated, about 55 percent were unchanged, and over 4 percent were significantly degraded from daylighting. Similar results were yielded by analysis of aluminum and manganese loads. In regards to iron, acidity, manganese, and aluminum, the percent of discharges that were degraded during daylighting was never greater than 6.5.

Analysis of the implementation of special water handling facilities, tabulated in Appendix B, yielded similar results. However, this category includes both surface and ground-water handling facilities. Fifty percent of the 22 affected discharges exhibited an improvement or elimination for acidity loading with the remainder showing no significant change. Almost 48 percent of 23

discharges exhibited an improvement or elimination with an additional 48 percent showing no significant change for iron loading. Slightly over 4 percent were significantly degraded in regards to iron loads. Manganese loadings showed that 47 percent of the 20 affected discharges were improved or eliminated and 42 percent were unchanged. The analysis indicated that slightly over 10 percent of the discharges had been degraded in regards to manganese loadings. Aluminum loads exhibited similar results with the bulk of the discharges (73 percent) being unchanged and none showing degradation.

Overall, the analyses of acidity, iron, manganese, and aluminum loading data from these completed remining sites indicates that between 90 and 100 percent of the discharges will show no degradation from daylighting or special water handling. Additionally, between 27 and 50 percent of the discharges will be improved or completely eliminated. These efficiency numbers can be improved with the specific tailoring of the BMPs to reduce or exclude lateral ground-water movement.

1.2.5 Summary

Previous studies have shown that the extent of pollution reduction from remining is largely dependent on reducing the discharge rate, which in turn is dependent on the controlling the infiltration of ground water into the backfill. The commonly-observed positive correlation between flow and loading rates illustrates this close relationship. BMPs designed and implemented to prevent ground-water infiltration from adjacent areas will be successful in reducing the pollution load and in some cases may completely eliminate the discharge.

Case Studies 1 and 2 illustrate that underground mine daylighting, entry and highwall sealing, and other ground water-controlling BMPs can yield mixed results unless differences in precipitation rates are taken into account and the post-remining monitoring period is of sufficient length to accurately reflect site conditions. However, it is well known that these BMPs, when properly implemented, will reduce the contaminant load from remining operations.

1.3 Sediment Control and Revegetation

Erosion and sediment deposition caused by weathering and precipitation are natural processes that can be accelerated in disturbed watersheds. Disturbances such as surface coal mining involve the removal of vegetation, soil, and rock. Spoil or highwall surfaces create conditions highly vulnerable to erosion and result in adverse sediment deposition that can clog streams, increase the risk of flooding, damage irrigation systems, and destroy aquatic habitats. Sediment deposition in downslope areas can have adverse environmental impacts on watershed soil and vegetation. Abandoned surface mine land, spoil refuse and gob piles often have exposed surfaces that are vulnerable to erosion or conducive to high rates of storm water runoff resulting in increased problems of sedimentation in receiving streams. Re-exposing these abandoned sites during remining operations without concern for sediment control can cause serious solids loading and hydrologic imbalance. Successful implementation of erosion and sediment control BMPs are critical for ultimate landscape stability and receiving stream protection.

Theory

The implementation of the BMPs discussed in this section for management of surface water and ground water at remining operations also can form the basis for sediment control. If implemented properly, site hydrologic controls can serve to prevent erosion, solids loading into receiving waters, and unchecked sediment deposition. Likewise, if hydrologic controls are implemented without consideration for potential sedimentation, conditions leading to discharge of solids and sediment can rapidly increase and result in severe environmental degradation.

Remining and reclamation of abandoned mine lands typically require techniques that involve regrading to approximate original contour, replacing topsoil, applying vegetation amendments, and constructing erosion-control structures. The resulting reclamation often is aesthetically pleasing, but can result in an artificial drainage system that can be problematic and accelerate

erosion as natural drainage systems are re-established. If reclamation techniques fail to consider natural drainage patterns and surface water flow characteristics, conditions can become worse than those that existed prior to implementation of these techniques. Sedimentation and erosion problems can be alleviated by proper implementation of some or all of the BMPs discussed in this section.

Site Assessment

Prior to implementation of BMPs to control erosion and suspended solids loading, sites should be assessed to determine existing drainage patterns and topography, to quantify effects of storm runoff and the yield of coarse- and fine-grained sediment, and to determine morphologic evolution of gullies. Natural drainage patterns can be determined using before and after maps and profiles, aerial photography, site mining history information and water quality data. Determinations should also consider precipitation frequency, duration, and intensity. This information can be used to indicate locations where the implementation of sediment control BMPs will be most effective.

In addition to determining sedimentation patterns, it is important to determine the quantity of sedimentation that can be expected. An estimate of sediment erosion and deposition can be derived over time using water samples, sediment traps or sediment accumulation markers. Empirical equations also can be used to estimate the potential for and expected rate of erosion. The Universal Soil Loss Equation (USLE) was developed as a means to predict sediment loss from watersheds and can be used to estimate sediment yield produced by rill or sheet erosion in field areas. A Revised Universal Soil Loss Equation (RUSLE) was developed to estimate quantities of soil that can be lost due to erosion in larger, steeply sloped areas. Predicted soil loss is calculated using the following equation (OSMRE, 1998, PA DEP, 1999, Renard and others, 1997):

$$A = RKLSCP$$

Where:

- A** = Computed Soil Loss (Annual Soil Loss as tons/acre/year)
- R** = Climatic Erosivity or Rainfall erosion index - a measure of the erosive force and intensity of a specific rainfall or the normal yearly rainfall for specific climatic regions
- K** = Soil Erodibility Factor - Ability of soils to resist erosive energy of rain. A measure of the erosion potential for a specific soil type based on inherent physical properties (particle size, organic matter, aggregate stability, permeability). Soils with a K value of 0.17 or less are considered slightly erodible, and those with a K value of 0.45 or higher are highly erodible. Soils in disturbed areas can be more easily eroded regardless of the listed K value for the soil type because the structure has been changed.
- LS** = Steepness Factor - Combination factor for slope length and gradient
- C** = Cover and Management Factor - Type of vegetation and cover. The ratio of soil loss from a field with specific cropping relative to that from the fallow condition on which the factor K is evaluated.
- P** = Support Practice - Erosion control practice factor, the ratio of soil loss under specified management practices.

RUSLE can be used to predict soil loss from areas that have been subjected to a full spectrum of land manipulation and reclamation activities and has been designed to accommodate undisturbed soil, spoil, and soil-substitute material, percent rock cover, random surface roughness, mulches, vegetation types, and mechanical equipment effects on soil roughness, hillslope shape, and surface manipulation including contour furrows, terraces, and strips of close-growing vegetation and buffers. It is important to note that RUSLE estimates soil loss caused by raindrop impact and overland flow in addition to rill erosion, but does not estimate gully or stream-channel erosion.

To establish successful vegetation, the soil loss rate should be minimized. Keeping the soil loss rate below 15 tons/acre for the first year after reclamation should, if surface water controls are included, allow the establishment of successful vegetation (PA DEP, 1999). For successful establishment of vegetative cover on abandoned mine land or redisturbed surfaces, the addition of soil amendments (e.g., soil substitutes, biosolids, etc.) may be necessary. Following regrading, final texture samples should be taken at a rate appropriate for site representation and analyzed for: pH, acid-base account, and fertility ratings for phosphorous, potassium, nitrogen, and magnesium. The necessity of amendments such as limestone, nitrogen, available phosphorous (P_2O_5), and potash (K_2O) can be determined from these analytical results. Additional analyses that can be performed for further determination of site characteristics include: percent sand, silt and clay, textural classification, and water-holding capacity. This information can be used to assist in determination of the extent of final grading, cover preparation, and soil water retention amendments that should be implemented or added.

1.3.1 Implementation Guidelines

The intention of BMPs for control of sedimentation is to minimize erosion caused by wind and water. A remining sediment control plan should demonstrate that all exposed or disturbed areas are stabilized to the greatest extent possible. Operational BMP measures that can be implemented with this intent include:

- Disturbing the smallest practicable area at any one time during the remining operation,
- Implementing progressive backfilling, grading, and prompt revegetation,
- Stabilizing all exposed surface areas,
- Stabilizing backfill material to control the rate and volume of runoff,
- Diverting runoff from undisturbed lands away from or through disturbed areas using protected channels or pipes, and
- Using terraces, check dams, dugout ponds, straw dikes, rip rap, mulch, and other measures to control overland flow velocity and volume, trap sediment in runoff or protect the disturbed land surface from erosion (e.g. silt fences and vegetative sediment filters).

Construction of terraces, diversion ditches, and other grading/drainage control measures can be utilized to help prevent erosion and ensure slope stability. It is recommended that drainage ditches, spillways or channels are designed to be non-erodible, to carry sustained flows, or, if sustained flows are not expected, to be earth or grass-lined and designed to carry short-term, periodic flows at non-erosive velocities. Design should demonstrate that erosion will be controlled, deepening or enlargement of stream channels will be prevented, and disturbance of the hydrologic balance will be minimal. All slopes and exposed highwalls should be stable and protected against surface erosion. Slopes and highwall faces should be vegetated, rip rapped, or otherwise stabilized. Hydrologic diversions and flow controls should be free of sod, large roots, frozen soil and acid- or toxic-forming coal processing waste, and should be compacted properly according to applicable regulatory standards. Additional contributions of sediment to streamflow and runoff outside the permit area should be prevented to the greatest extent possible.

Certain sediment control BMPs already are an integral part of mining operations and do not require additional engineering designs or construction. These BMPs are recommended for implementation during pre-, active and post-remining activities, and often are incorporated into remining BMP implementation plans (Appendix A, EPA Remining Database, 1999). These BMPs include:

- Streams, channels, checks dams, diversion ditches, and drains should be inspected regularly and accumulated sediment removed. Channels and ditches should be seeded and mulched immediately after completion, if completion corresponds to regional growing seasons.
- Backfilling and regrading should be concurrent with coal removal and should follow removal as soon as is technically feasible. Final grading should be performed during normal seeding seasons to eliminate spoil piles and depressions at a time expeditious for prompt establishment of vegetation.

- Exposed and rounded surfaces should be mulched and vegetated immediately following final grading. It is recommended that mulch be anchored in the topsoil and that vegetation be planted immediately after topsoil grading.
- Areas should be reclaimed to an appropriate grade (slopes should not exceed the angle of repose or the slope necessary to achieve minimum long-term stability and prevent slides) to prevent surface-water impounding and promote drainage and stability. All final grading should be completed along the contour. Terrace-type backfilling and grading works to prevent slides and sedimentation while promoting slope stability (this also maximizes coal recovery and eliminates exposed highwalls and spoil piles).
- Unstable-abandoned spoil and highwalls should be eliminated to the greatest extent possible. Care should be taken if the remining operation requires disturbance of existing benches and highwalls that have well-established vegetation and drainage patterns. Re-affecting abandoned mine lands that are well-vegetated and stabilized should be avoided to the greatest extent possible.
- Overburden and topsoil stockpiles that are not being used for topsoil or the establishment of vegetation should be located to minimize exposure and should be seeded with annual plants when needed to prevent excessive erosion.
- Topsoil material should be redistributed on graded areas in a manner which protects the material from wind and water erosion before it is seeded and planted. Compaction of surface topsoil materials should be such as to minimize erosion and surface water infiltration, yet promote establishment of vegetation.
- Streams and runoff should be directed away from spoil, refuse and overburden piles, exposed surfaces, and unstable slopes.

Site Stabilization

Minimization of the amount of disturbance during remining operations will decrease the amount of soil and sediment eroding from the site, and can decrease the amount of additional controls or BMPs that will be required. Operations should only disturb portions of the site necessary for coal recovery. Operations also can be staged to ensure that only a small portion of the site is disturbed at any given time. If possible, portions should be remined, regraded and seeded prior to disturbance of the next area.

Preserving existing vegetation or revegetating disturbed soil as soon as possible after disturbance is the most effective way to control erosion (EPA, 1992). Vegetative and other site stabilization practices can be either temporary or permanent. Temporary controls provide a cover for exposed or disturbed areas for short periods of time or until permanent erosion controls are established.

Erosion and sedimentation can be minimized by removing as little overburden or topsoil as possible during remining operations, and by having sediment controls in place before operations begin. Any possible preservation of natural vegetation should be planned before site disturbance begins. The advantages of such preservation include the capacity for natural vegetation to handle higher quantities of surface water runoff.

Revegetation

Revegetation can be one of the most effective BMPs for achieving erosion control. By functioning to shield surfaces from precipitation, attenuate surface water runoff velocity, hold soil particles in place and maintain the soil's capacity to absorb water while preventing deeper infiltration, the establishment of vegetation can stabilize disturbed areas with respect to erosion, and surface water infiltration, and attenuate AMD formation. Implementation of revegetation consists of seedbed preparation, fertilizing, liming, seeding, mulching, and maintenance.

Biosolids are a low-cost alternative to the use of commercially available lime and fertilizers. The biosolids typically used on remining sites are sewage treatment sludge. However, other biosolids can be obtained from paper mill waste and from other industries. Biosolids are available in various forms, but the most common is anaerobically digested materials that require an additional lime amendment.

Abandoned mine lands frequently have large areas with little or no topsoil, devoid of organic matter, and micro-organisms. Biosolids use is beneficial in terms of creating a soil substitute and improving revegetation, but also in developing soil structure through the addition of organic matter which will foster a microbial community needed for the decomposition of biomass and other biochemical activities that take place in soil.

Vegetative cover can be grass, trees or shrubs, but grasses are the most frequently used because they grow quickly, providing erosion protection sometimes within days. Permanent seeding and planting is appropriate for any graded or cleared area where long-lived plant cover is desired, and is especially effective in areas where soils may be unstable because of soil texture and structure, a high water table, high winds, or steep slopes.

Typical implementation and maintenance of revegetation operations at 51 mining sites in Alabama, Kentucky, Pennsylvania, Tennessee, Virginia, and West Virginia, are summarized in Table 1.3.1a.

Table 1.3.1a: Revegetation Practices and Maintenance (Appendix A, EPA Remining Database, 1999)

<u>Revegetation Plan</u>	
-	Systematic sample collection and analysis of topsoil, subsoil, and overburden materials to determine the type and amount of soil amendments necessary to maintain vegetative growth.
-	Topsoil placement and seeding occur no later than the first period of favorable planting after backfilling and grading. Disturbed areas are seeded/planted as contemporaneously as practicable with completion of backfilling and grading. Backfilled areas prepared for seeding during adverse climatic conditions are seeded with an appropriate temporary cover until permanent cover is established (cover of small grain, grasses, or legumes can be installed until a permanent cover is established).
-	Disturbed areas are seeded in such a manner as to stabilize erosion and establish a diverse, effective and permanent vegetative cover, preferably of a native seasonal variety or species that supports the approved post-mining land use.
-	Regraded areas are disced prior to application of fertilizer, lime and seed mixture. Fertilizer mixture is applied as determined necessary by soil sample analyses. Treatment to neutralize soil acidity is performed by adding agricultural grade lime at a rate determined by soil tests. Neutralizers are applied immediately after regrading. A minimum pH of 5.5 is maintained.
-	Mulch is applied to promote germination, control erosion, increase moisture retention, insulate against solar heat, and supply additional organic matter. Straw, hay, or wood fiber mulch are applied at approximately 1.0 to 2.5 tons/acre. Small cereal grains have been used in lieu of mulch (small grains absorb moisture and act as a soil stabilizer and protective cover until a suitable growing season).
-	Conventional equipment is used: broadcast spreader, hay blower, hydroseeder, discs, cyclone spreaders, grain drills, or hand broadcasting. Excess compaction is prevented by using only tracked equipment. Rubber tired vehicles are kept off reconstructed seedbeds.
<u>Maintenance</u>	
-	Vegetative cover is inspected regularly. Areas are checked and maintained until permanent cover is satisfactory. Bare spots are reseeded, and nutrients are added to improve growth and coverage. Areas that are damaged due to abnormal weather conditions, disease, or pests are repaired.
-	Unwanted rills and gullies are repaired with soil material. If necessary, the area is scarified and (in severe cases) back-bladed before reseeding and mulching.
-	Revegetation success is determined by systematic sampling, typically at a minimum of 1 percent of the area. Aerial photography can be used to determine success (typically at the 1 percent level - or higher if necessary). Standard of Success (SOS) for revegetation is based on percent of existing ground cover or achievement of vegetation adequate to control erosion.

Maintenance (cont.)

- Periodic mowing is performed to allow grasses and legumes a greater chance of growth and survival. Plants are not grazed or harvested until well-established.
- Previously seeded areas are reseeded as necessary, on an annual basis until covered with an adequate vegetal cover to prevent accelerated erosion. Areas where herbaceous cover is bare or sparsely covered after 6-12 months are re-limed and/or re-fertilized as necessary to promote vegetative growth, then reseeded and mulched.

The amount of runoff generated from well vegetated areas is considerably reduced and is of better quality than from unvegetated areas. However, it is not possible, based on data currently available, to quantify the water quality benefits of the vegetative coverings as a BMP (EPA, 1996).

Direct Revegetation

Direct revegetation is an alternative to reclamation techniques that are designed to resculpture the existing topography. During direct revegetation, grading is avoided to prevent exposure of deeper, unweathered acid-forming materials and emphasis is placed on preservation of the weathered surficial materials and the network of natural drainage. Direct revegetation is generally low-cost and eliminates the acidity and potential acidity remaining in exposed surface layers by treatment with limestone or other alkaline materials. Once the surficial acidity is removed, natural processes that are aided and accelerated by application of fertilizer, mulch, and other organic amendments, can be relied upon to establish permanent vegetative cover (Nawrot and others, 1988). Work may be required for several (typically three) successive growing seasons, in order to ensure the establishment of vegetation across the entire area to be reclaimed (Olyphant, 1995).

Direct revegetation commonly requires the addition of lime and fertilizers to mine spoil or coal refuse piles that are devoid of vegetation. Biosolids can be easily employed in cases of direct revegetation. The material can be spread by use of a hydroseeder or farm equipment. Areas requiring direct revegetation are often poorly accessible due to steep and unstable slopes.

Therefore, the ability to spread biosolids from a secure distance makes it ideal for direct revegetation application. Biosolids, in many cases, form the basis of soil material or augment what little soil exists on the site.

Biosolids were used at numerous remining sites in Pennsylvania where little soil existed prior to remining or where, if soil did exist, it was lost due to burial or erosion from pre-SMCRA mining. Increases in plant growth and density can be dramatically improved using biosolids.

Channel, Ditch and Gully Stabilization

Stabilization of channels, ditches, and gullies at remining sites, whether constructed for surface water and erosion control or unwanted, is imperative for controlling sedimentation. In general, formation of unwanted gullies should be avoided. These BMPs are recommended when vegetative stabilization practices are not practical and where stream banks are subject to heavy erosion from increased flows or disturbances. If unwanted or naturally-formed gullies are well-established, stabilization may prove more effective than removal. Gullies that are deeper than nine inches may form in regraded areas and should be filled, graded, and reseeded. Rills or gullies of lesser size may have a disruptive effect on post-mining land use or may add to erosion and sedimentation and should be filled, graded, and seeded (Appendix A, EPA Remining Database, 1999 VA(2)).

It is recommended that permanent channels and gullies be designed and constructed based on 100 year, 24 hour storm event. Channels and gullies can be stabilized and protected from eroding forces by the implementation of linings and/or check dams. Linings can be constructed of grass, rock, rip rap, or concrete. Check dams can be constructed with staked straw bales, wood, or rock. Although channel linings and check dams can trap small amounts of sediment, their primary purpose is to reduce the velocity of storm water flow, thus abating additional erosion.

Channel Linings

Erosion is a serious problem associated with channels and other water control structures. Sediment loads from eroded channels can cause numerous sediment and hydraulic problems and decrease the effectiveness of other sediment control measures. Depending on flow velocities, channel linings may be required to prevent channel erosion (MD DNR, 1989).

Due to the ease of construction and low cost, a vegetated channel lining is one of the most cost-effective ways of reducing channel erosion and is frequently used on diversion ditches. A well-established grass can protect the channel from erosive flow velocities of up to 6 feet per second (fps). Shorter meadow-type grasses with short, flexible blades can withstand a maximum permissible velocity of 5 fps. Bunch grasses or sparse cover provides only marginally better erosion protection than a well constructed earthen channel. For prevention of erosion, the Commonwealth of Kentucky (Kentucky, 1996) recommends that channels having a peak discharge design velocity of less than 5 fps be lined with grass species that are effective against erosion (e.g. Tall Fescue, Reed Canarygrass, Bermudagrass, and Kentucky Bluegrass). Channels having discharge velocities of 5 fps or greater should be lined with rip rap or other non-erodible, non-degradable materials unless the ditch is located in solid rock. Pennsylvania DEP (PA DEP, 1999) recommends a maximum velocity of 3 fps if only sparse cover can be established or maintained (because of shale, soils, or climate); a velocity of 3 to 4 fps if the vegetation is established by seeding (under normal conditions); and a velocity of 4 to 5 fps only in areas where a dense, vigorous sod is obtained quickly or if runoff can be diverted out of the waterway while vegetation is being established.

Vegetative linings typically begin eroding the base of channels, and once started, will continue until an erosion resistant layer is encountered. If it becomes evident that erosion of a channel bottom is occurring, rock or stone rip rap lining should be placed in the eroded areas. Rip rap lining should be durable and should be free of acid-forming materials. Generally, rip rap composed of varying sizes of stones is preferred over rip rap that is uniform, not only because it is less expensive, but because the varying stone size promotes natural settling and grading to form a

better seal. In addition, rectangularly shaped stone is preferred for its durability. Smooth or rounded stones should not be used (MD DNR, 1989). A good recommendation is the use of a well-graded mixture down to the one-inch particle size such that 50 percent of the mixture by weight is no larger than the median stone size. Rip rap layers should have a minimum thickness of 1.5 times the maximum stone diameter or no less than six inches, whichever is the lesser value. Channel banks should be protected to a height equal to the maximum depth of flow (Kentucky, 1996). Rip rap used in diversion ditches and pond spillways should consist of durable sandstone or limestone exhibiting a Slake-Durability Index of 85 or greater. The rip rap should be well-graded with the maximum stone size D(100) equal to the blanket thickness and the median stone size DD(50) equal to one half the blanket thickness (Appendix A, EPA Remining Database, 1999 VA(7)).

Check Dams

The purpose of check dams is to reduce the velocity of concentrated surface-water flow until diversion ditches or gullies are properly vegetated. Check dams can be constructed of straw bales, logs, rocks (Figure 1.3.1a), or other readily available materials, and should be designed so that water crosses only through a weir or other outlet and never flows along the top or the outside of the dam (Kentucky, 1996). The distance between check dams varies depending on the slope, with a closer spacing when slopes are steeper. Materials used should be relatively impermeable and of appropriate size, angularity, and density. They should be contained in anchored wire mesh or gabions, or staked to prevent flowing water from transporting them (Figure 1.3.1b).

The material used depends on the size and type of flow that is expected. Straw bale check dams generally are suitable for sediment control where concentrated flows do not develop. The efficiency of straw bale dams is limited by slope length and gradient. Straw or hay bales should be secured with stakes. Log check dams can be used in channels and generally are more effective and stable than straw bale barriers. It is recommended that logs be four to six inches in diameter, driven sufficiently beneath the channel floor, and stand perpendicular to the plane of the channel cross section, with no space between logs (Kentucky, 1996). It also is recommended that rip rap

or shorter, wider logs on the downstream side be installed for stability. Rock check dams and straw bales allow water to pass through, controlling sediment movement through filtration and flow control. The size of the stone used in a rock check dam varies, with rock size increasing as flow velocity and discharge volume increase. For most rock check dams, the National Crushed Stone Association no. R-4 stone (3 to 12 inches, 6 inch average) is a suitable stone size (PA DEP, 1999). Filter stone applied to the upstream face of check dams can improve sediment trapping efficiency. Regular removal of sediment that accumulates behind the check dam is imperative for maintenance of efficiency, control of surface water flow, and avoidance of worsening conditions. Check dams also can be built in series, as necessary.

Figure 1.3.1a: Example of a Rock Check Dam (Kentucky, 1996)

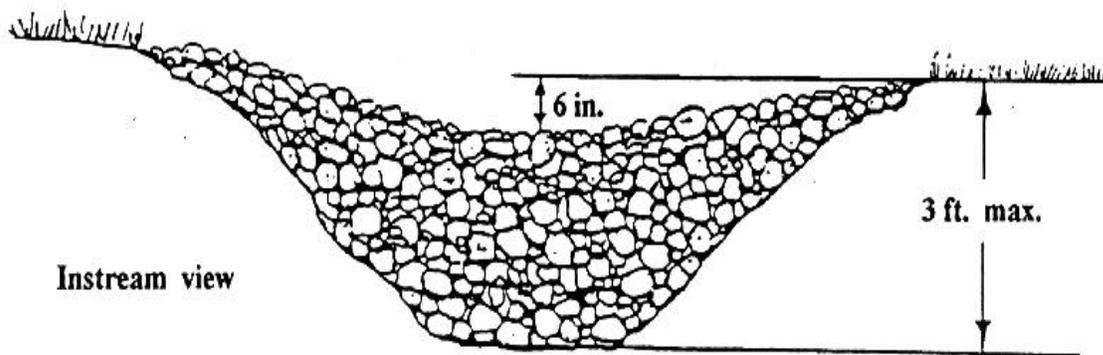
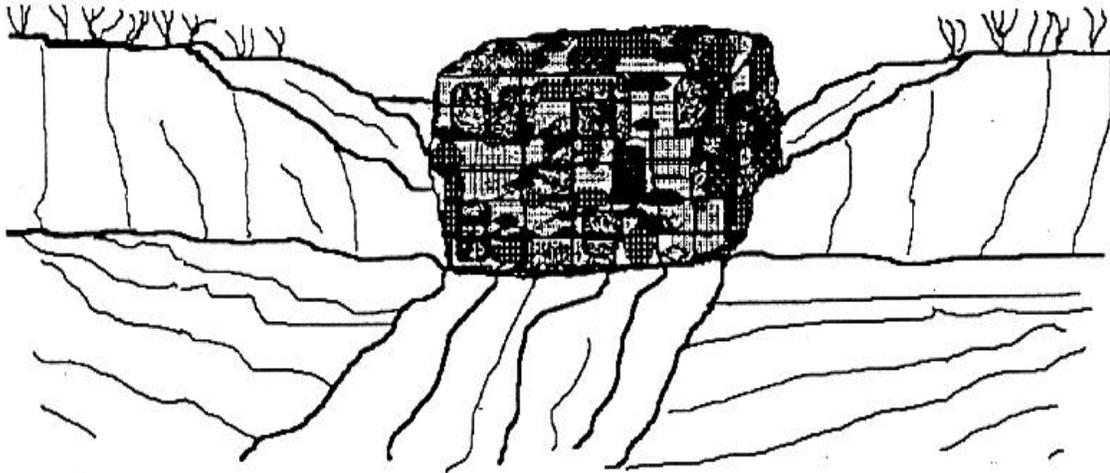


Figure 1.3.1b: Example of a Gabion Check Dam (Kentucky, 1996)

Silt Fences

Silt fences are used as temporary sediment barriers and are commonly constructed of burlap or synthetic materials stretched between and attached to supporting posts. The purpose of silt fencing is to detain sediment-laden, overland (sheet) flow long enough to allow the larger size particles to settle out and to filter out silt-sized particles. Because the screen sizes of synthetic screen fences will vary according to the manufacturer, these fences usually do not have the strength to support impounded water and are limited to control of overland runoff. Common problems associated with silt or filter fabric fences usually result from inappropriate installation such as placement in areas of concentrated flows or steep slopes and placement down rather than along contours. These fences work best when placed on areas with zero slope. Because this often is not possible, flow should be otherwise reduced by the downslope emplacement of hay bales, mulching, or breaking the length of installation into separate sections that will not allow significant flow volumes. Silt fencing is appropriate for sediment control immediately upstream of the point(s) of runoff discharge, before a flow becomes concentrated, or below disturbed areas where runoff may occur in the form of overland flow.

Gradient Terraces

Gradient terraces can be used to control slope lengths, minimize sediment movement, and, on a site-specific basis, to address particular erosion problem spots according to need. Terraces are typically earth embankments or ridge-and-channels constructed along the face of a slope at regular intervals and at a positive grade. These BMPs often help stabilize steeply sloped areas until vegetation can be established and reduce erosion damage by capturing surface runoff and directing it to a stable outlet at a speed necessary to minimize erosion. Terrace locations and spacing can be determined following general grading and location of problem areas. It is recommended that terraces constructed on slopes are not excessive in width and have outer slopes no greater than 50 percent.

Design Criteria

General

- Design should approximate natural drainage as closely as possible.
- Sediment-control structures should be chosen according to review of existing topography, flow direction and volume, outlet location, and feasibility of construction.
- Sediment control structures should be constructed on stable ground.
- Use of costly earth-moving equipment should be minimized.
- Weathered, vegetated and highly established portions of landscape should be preserved to the greatest extent possible.

Revegetation

- Volunteer, natural vegetation should be encouraged, and where possible, undisturbed.

Channel, Ditch and Gully Stabilization

- Liner materials should not contain acid-forming materials.

- Stabilization should be supported properly. Potential for stream bottom and sides to erode should be considered.
- Vegetation-lined ditches should be limited to velocities of 4 to 5 fps, unless documentation is provided that runoff will be diverted elsewhere while vegetation is being established.
- Permanent structures should be designed to handle expected flood conditions.

Check Dams

- Should be used only in small open channels which will not be overtopped by flow once the dams are constructed.
- Check dams should be anchored to prevent failure.
- Dams should be sized according to projected flows.
- The center of the dam should be lower than the edges.
- Straws bale barriers should be placed at zero percent grade, with the ends extended up the side slopes so that all runoff above the barrier is contained in the barrier.
- Stones should be placed by hand or using appropriate machinery, and should not be dumped in place.

Silt Fences

- Support posts should be strong and durable.
- Filter material should be able to retain at least 75 percent of the sediment.
- Fences should be installed in undisturbed ground, and stability should be reinforced with rope or rip rap.
- Adjoining sections of filter fabric should be overlapped and folded.
- Bottom edge should be tied or anchored into the ground to prevent underflow.
- Maintenance should be performed as needed, and material replaced when bulges or tears develop.

Terraces

- Terraces, in general, should not be excessive in width or have outer slopes greater than 50 percent.
- Utilize diversion ditches as necessary, while a vegetative cover is being established.
- Terraces should be designed with adequate outlets, such as a grassed waterway or vegetated area, to direct runoff to a point not causing additional erosion.

1.3.2 Verification of Success or Failure

Implementation Checklist

Revegetation

- Vegetation should be maintained through cutting, fertilizing and reseeding if needed.
- Vegetative success should be determined by a systematic sampling and plant count, and if necessary, aerial photography. Success should be measured on the basis of adequate vegetative cover which shall be defined as a vegetative cover capable of self-regeneration and plant succession, and sufficient to control soil erosion.
- Established vegetation should be inspected periodically for scouring. Scoured areas should be reseeded immediately.

Channel, Ditch and Gully Stabilization

- Inspect regularly and after each major storm event for: sediment buildup, scouring, blockage and lining damage or movement.
- If excessive scouring or erosion occurs in ditches or channels, they should be lined with rock rip rap or netting immediately.
- Sediment build up usually occurs in areas of low-flow velocities allowing particles to settle. Grade should be checked in these areas since low-flow velocities may mean the channel is undersized.

- Rip rap stones that have moved should be replaced and the rip rap fortified if undercutting has occurred.

Check Dams

- Inspect check dams regularly and after significant precipitation events for damage and sediment accumulation.
- Accumulated sediment should be removed from behind the dams and erosive damage restored after each storm or when half the original dam height is reached.
- The length of straw bale barriers should be inspected on a periodic basis to look for problem areas. Eroded areas should be regraded, accumulated sediment removed, and the barrier repaired to maintain effectiveness.
- Stone should be replaced as necessary to maintain correct dam height.

Silt Fences

- Silt fences should be inspected daily during periods of prolonged rainfall, immediately after each rainfall event, and weekly during periods of no rainfall.
- Required repairs should be made immediately.
- Sediment should be removed once it reaches one-third to one-half the height of the filter fence.
- Filter fences should not be removed until the upslope area has been permanently stabilized. Sediment deposits remaining after the filter fence has been removed should be graded, prepared and seeded.

Terraces

- Terraces should be inspected regularly at least once a year and after major storms.
- Proper vegetation and stabilization practices should be implemented during construction.

1.3.3 Literature Review / Case Studies

Case Study 1 (Harper and Olyphant, 1993; Olyphant and Harper, 1995; Carlson and Olyphant, 1996)

Direct Revegetation

Coal refuse is often an acid-forming material containing high concentrations of pyrite (\gg 0.50 percent total sulfur). If present, the oxidation of pyrite causes acidification of the soil, and acidification in turn, greatly inhibits vegetation. Substantial erosion and sedimentation occur due to poor or complete lack of vegetation on abandoned surface mine lands and coal refuse piles. Erosion is further accelerated by steep slopes common to some abandoned mine sites. Olyphant and Harper (1995) observed that direct revegetation of abandoned pyritic coal refuse piles can successfully reduce the sediment load as well as improve the water quality of the runoff effluent from abandoned mine lands.

Direct revegetation was conducted on abandoned pre-SMCRA coal refuse piles located in Sullivan County, Indiana (Harper and Olyphant, 1993; Olyphant and Harper, 1995; and Carlson and Olyphant, 1996). Prior to revegetation, these piles were characterized by “severe and rapid erosion” and high pyritic content (up to 4.4 percent by weight). The colluvial material “derived from gully side slopes” built up through the winter months. This material was washed out during the spring followed by “erosional downcutting” through the summer and fall. Yearly backcutting of the gullies ranged from 2.5 to 4.6 centimeters with an interfluvial lowering of 0.4 centimeters. The volume of sediment yielded by these gullies was approximately four fold that of the watershed as a whole and about 10 times that of adjacent interfluvial areas. Yearly sedimentation yield was over 10 kg/m² (Olyphant and Harper, 1995).

In order to treat the acidity of the surficial refuse and allow plant growth, limestone was directly discd into the refuse without regrading the existing surface. Fertilizer was also broadcast over portions of the site to promote the vegetative cover. Additionally, small rip rap check dams and water bars were installed to prevent erosion and promote infiltration of precipitation. From 1990

to 1992, 100 to 210 tons per acre of agricultural limestone was disced to a depth of 6 inches into the refuse. Fertilizer was applied in the spring of 1991 and 1992 at rates of 100 lbs per acre of N₂, 150 lbs per acre of P₂O₂, and 350 lbs per acre of K₂O. The refuse was initially planted with a rye-nurse crop. Additionally, a permanent cover of Kentucky 31 fescue, bristly locust, and black locust was highly successful. Direct vegetation of weathered, undisturbed refuse with a pH less than 3.8 and pyrite concentrations less than 0.84 percent, resulted in successful stabilization (Harper and Olyphant, 1993). Within 18 months, the site had a diverse dense growth of planted and volunteer vegetation (Olyphant and Harper, 1995).

The rip rap check dams were installed by “end-dumping” between 5 and 185 tons of rock directly into the upper parts of erosion gullies. Erosion netting and water bars were also used to control erosion on steep-slope areas, where additional time and effort is required to achieve sufficient vegetative cover to inhibit erosion.

The remedial work (direct planting, check dams, and water bars) resulted in increased precipitation infiltration (decreased runoff), reduced erosion and sedimentation, and an improvement in the runoff-water quality. Runoff decreased by 56.7 percent, from 30 to 13 percent of the precipitation. The increased infiltration resulted in a higher moisture content in the root zone, especially during dry periods. Coarse sediment yield prior to vegetation and the implementation of sediment controls comprised more than 50 percent of the total sediment. Afterward, coarse-grained sediments were virtually nonexistent. Fine-grained sediments declined from 4.5 kg/m² to 0.3 kg/m², or 93.3 percent. The acidity of the runoff improved from being occasionally over 700 mg/L to an average alkalinity of 75 mg/L (Olyphant and Harper, 1995). However, no alkalinity was observed in the refuse pore water below a depth of 1.7 feet (Harper and Olyphant, 1993).

Case Study 2 - Keel Branch, VA (Zipper and others, 1992)

The study area was an abandoned surface and underground coal mining site in Dickenson County, Virginia. The surface mining occurred between 1955 and 1958. “Shoot and shove” mining operations of that period produced a terrain consisting of exposed highwalls, more or less

level benches, and steep spoiled outcrops. Abandoned mine land areas included approximately 170 acres and 8,000 linear feet of outcrop-bench-highwall terrain. Highwalls from 50 to 100 feet high remained easily visible with evidence of some sloughing of highwall materials. Vegetative cover of the benches varied from dense to barren. The barren areas are associated with “burn out” from acidic coal fines. The outcrops were the main source of major environmental problems, with surface inclinations commonly exceeding 30° and extremely sloped areas nearing 40°. Adverse environmental impacts on watershed soil and vegetation was verified by the deterioration of natural forest areas directly below outcrops, caused by sediment movement from higher elevations downward toward the stream. A mining company was interested in remining coal from abandoned deep mine pillars and solid-coal sections that had not been surface mined, but was concerned about environmental liabilities (Zipper and others, 1992).

The goal of the study was to identify and compare the environmental effects of four remining and reclamation options. The objective was to estimate the reduction in soil loss and sediment yield likely to be achieved by various remining and reclamation strategies, relative to existing conditions using a modified Universal Soil Loss Equation model in a Geographic Information System (GIS) environment. The study evaluated three remining options and one AML-funded reclamation option and compared them to a “do-nothing” strategy. The remining options considered were:

Remnant Recovery: a technique frequently used to mine the remaining coal reserves from abandoned bench-highwall-outcrop terrain in southwestern Virginia, eastern Kentucky and southern West Virginia. The mine operator employs conventional second-cut remining, taking an additional cut from the highwall to extract coal from the most profitable areas. Spoil from the second-cut is used to reclaim the exposed highwall segment to the maximum extent technically practical. The reclaimed site is characterized as a steeply sloped highwall backfill, which may be adjacent to exposed highwalls remaining from unreclaimed pre-SMCRA operations. Existing spoil in the outcrop areas is not re-affected (Zipper and others, 1992).

Conventional Second-Cut Contour: is also commonly used in steeply-sloped Appalachian areas and similar to remnant recovery, except rather than mining only the most profitable areas, additional cuts are taken from a relatively long, continuous portion of the highwall. This method also allows for reclamation of all exposed highwall to steeply sloped backfill contours. As with remnant recovery, outslope spoils are avoided to the greatest extent possible (Zipper and others, 1992).

Innovative Remining: designed to maximize reclamation effectiveness as allowed by the scope of the remaining minable coal reserves. The key to this plan is to apply virgin cuts to a coal seam at the base of the spoil slope as well as additional cuts into the existing highwall of a higher coal seam. In the process of reclamation, the spoil on the outslope will be eliminated. Critical to this plan is that the highest portions of the upper highwall do not have to be completely reclaimed. This is important because such reclamation can be cost prohibitive for remining operations. Much of the temporary sediment controls are placed down gradient in or near the headwaters of the adjacent streams. The main benefit of this methodology is that the problems caused by the spoil outsoles are eliminated (Zipper and others, 1992).

AML Reclamation: an option in which no additional coal is mined, the outslope area is regraded and the spoil is replaced into the existing open pit. Complete highwall elimination is unlikely, because the amount of spoil on the outslope is insufficient. However, the exposed strip bench is covered. Actual AML reclamation is unlikely at the study site because it has been assigned the lowest AML Fund priority number (3) (Zipper and others, 1992).

Roughly 40 percent of the abandoned mined areas of the site (mainly the steep outsoles) presently yield 95 percent of the sediment. Most of the study area (77 percent) has estimated soil losses of “stable conditions”, which are 0 to 1 ton per year. Approximately 8 percent of the AML area has soil loss potentials of between 20 and 50 tons per year. Soil losses exceeding 50 tons per year were determined for 2.6 percent of the AML area. Of the total soil loss, 60 percent was redeposited on the land surface, while the remaining 40 percent caused siltation of the streams.

Remnant recovery and conventional second-cut contour were determined to be the least effective reclamation techniques in terms of controlling erosion and sedimentation. Remnant recovery showed a soil loss reduction of 8 to 23 percent depending on the amount of vegetative cover of 60 and 95 percent respectively. Conventional second-cut contour fared slightly higher with soil loss reductions of 19 to 39 percent. The two reclamation methods that eliminate the outslope spoil performed the best. Innovative remining has predicted soil loss reductions ranging from 38 to 86 percent, while AML reclamation would yield soil loss reductions from 52 to 75 percent. Regardless of the reclamation technique analyzed the effectiveness improved with increasing ground cover (Zipper and others, 1992).

Critical to innovative reclamation is procurement of a variance to the complete highwall elimination requirement. With this type of reclamation, sedimentation is greatly reduced, a coal resource is utilized, and substantial reclamation is achieved.

1.3.4 Discussion

Typical sedimentation control BMPs entail slope regrading, revegetation, sediment trapping, and control of runoff. Successful control of erosion and sedimentation from remining operations may require innovative practices and controls in addition to those normally implemented. Existing unreclaimed conditions create distinct problems, especially in terms of erosion and sedimentation on steeply sloped spoil. Innovative techniques for remining and reclamation can be employed to mitigate erosion and sedimentation problems.

Benefits

- Implementation can require minimal labor. Sediment control BMPs are typically low cost and use conventional farming equipment.
- Can subsequently reduce availability or reactivity of acid-forming materials.
- Can subsequently be implemented to control site surface-water hydrology.
- Hydraulic and sediment control BMPs are often already permit requirements.

- Biosolids can provide nutrients and organic mater on sites with poor or nonexistent soils, thus enhancing plant growth.
- These BMPs often improve site aesthetics and can provide wildlife habitats.

Limitations

- If not designed, implemented, and maintained properly, severe and rapid erosion can occur as natural drainage networks are re-established.
- Steeply sloped areas may require intensive physical labor (not machine accessible).
- Establishment of vegetative covering should be coordinated with climatic conditions for proper establishment.
- Biosolids application rates may be limited by metals concentrations.
- BMP success is often dependent on climate and weather.

1.3.5 Summary

There are remining situations where the primary water quality concern is not necessarily the dissolved contaminant component or pH, but is instead suspended solids and the subsequent deposition of sediment into receiving streams. Surface mining prior to SMCRA commonly left unreclaimed spoil piles and open pits. Pre-SMCRA mining operations in steeply sloped areas tended to spoil the overburden downslope of the operation. Abandoned spoil piles and exposed surfaces have been weathering for decades and through natural processes, typically have been partially to completely revegetated. Whether or not these spoil piles are reaffected, considerable erosion and sedimentation may result during remining operations. Therefore, erosion and sedimentation control BMPs frequently require additional measures in addition to the standard controls.

Slope stabilization through control of precipitation runoff is a critical component of these BMP practices. If erosion can be prevented, sedimentation will be controlled. Runoff and associated erosion is controlled through the integration of engineered slopes (e.g., terraces), revegetation,

surface-water diversion through or away from spoil areas, sediment traps (e.g., silt fences, check dams, rip rap, dugout ponds), minimizing the amount of unreclaimed land at any given time, concurrent reclamation, and elimination of existing unstable spoil areas. Although significant sedimentation associated with remining is somewhat regional and is more prominent in steep slope areas, the problem is an important one. The BMPs discussed in this section have been successfully applied throughout the eastern Coalfields.

References

Ackman, T. E., J. R. Jones, and C. C. Hustwit, 1989. Stream Sealing to Reduce Infiltration into Underground Mines, Final Report, U.S. Bureau of Mines, Interagency Agreement No. J5160066 with the Office of Surface Mining Reclamation and Enforcement, Green Tree, PA, 108 p.

Ackman, T. E. and J. R. Jones, 1988. Stream Sealing to Reduce Surface Water Infiltration, U.S. Bureau of Mines Information Circular, IC9183, pp. 233-239.

Bell, A. V., M. D. Riley, and E. K. Yanful, 1994. Evaluation of a Composite Cover to Control Acid Waste Rock Pile Drainage. In the proceedings of International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage, vol 2 of 4, U.S. Bureau of Mines Special Publication SP 06B-94, pp. 113-121.

Booth, C.J., 1988. Interpretation of Well and Field Data in a Heterogeneous Layered Aquifer Setting, Appalachian Plateau, Ground Water, Vol. 26, No. 5, pp 596-606.

Borchers, J.W. and G.G. Wyrick, 1981. Application of Stress-Relief-Fracturing Concepts for Monitoring the Effects of Surface Mining of Ground Water in Appalachian Plateau Valleys. In the Proceedings of the Symposium of Surface Mining Hydrology, Sedimentology, and Reclamation, December 7-11, 1981, University of Kentucky, Lexington, KY, pp. 443-449.

Broman, P. G., P. Hagland, and E. Mattsson, 1991. Use of Sludge for Sealing Purposes in Dry Covers—Development and Field Experiences. In the Proceedings of the Second International Conference on the Abatement of Acidic Drainage, Montreal, Quebec, Canada, Tome 1, pp. 515-528.

Carlson, Christopher P. and Oylphant, Greg A., 1996. The Role of Gully Stabilization in Abandoned Mine Lands Reclamation. Environmental & Engineering Geoscience, Vol. II, No. 3, Fall 1996, pp. 393-405.

Caruccio, F.T. and G Geidel, 1986. Geologic Factors Affecting Mine Drainage Quality, In the Proceedings of A One-Day Conference Depositional Environment and Coal Hydrology, Clarion University, January 23, 1986. pp. 39-48.

Cederstrom, D.J., 1971. Hydrologic Effects of Strip Mining West of Appalachia. Mining Congress Journal, March, 1971, pp. 46-50.

EPRI, 1981. Coal Ash Disposal Manual, Second Edition, prepared by GAI Consultants, Inc. for the Electrical Power Research Institute, Palo Alto, CA, Section 2, pp37.

Freeze, R. A. and J. A. Cherry, 1979. GROUND WATER, Prentice-Hall, Inc., Englewood Cliffs, NJ, 604 p.

Gardner, M., 1998. Water Management Techniques on Surface Mining Sites, Chapter 16 of Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania, Pennsylvania Department of Environmental Protection, Harrisburg, PA, 11 p.

Gerencher, E. H., J. Y. Wong, R. van Dyke, and D. E. Konasewich, 1991. The Use of Mine Tailings in Concrete Surface Covers to Control Acid Mine Drainage in Waste Rock Dumps. In the Proceedings of the Second International Conference on the Abatement of Acidic Drainage, Montreal, Quebec, Canada, Tome 4, pp. 69-84.

Harper, Denver and Olyphant, Greg A, 1993. Direct Revegetation of Abandoned Coal-Refuse Deposits in Indiana: Its Effects on Hydrology, Chemistry, and Erosion. Final Report to the Indiana Division of Reclamation Concerning Research and Reclamation Feasibility Studies at the Friar Tuck Site, Sullivan and Greene Counties, Indiana. Indiana Geological Survey, 41 p

Hawkins, J. W., 1998a. Hydraulic Properties of Surface Mine Spoils of the Northern Appalachian Plateau. In the proceedings of 25th Anniversary and 15th Annual Meeting of the American Society for Surface Mining and Reclamation, St. Louis, MO, pp. 32-40.

Hawkins, J. W., 1998b. Hydrogeologic Characteristics of Surface-Mine Spoil, Chapter 3 of Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania, PA DEP, Harrisburg, pp. 3-1 to 3-11.

Hawkins, J. W., 1995a. Impacts on Ground Water Hydrology from Surface Coal Mining in Northern Appalachia, Proceedings of the 1995 Annual Meeting of the American Institute of Hydrology, Denver, CO.

Hawkins, J. W., 1995b. Characterization and Effectiveness of Remining Abandoned Coal Mines in Pennsylvania. U.S. Bureau of Mines, Report of Investigations-9562, 37 p.

Hawkins, J. W., 1994. Modeling of a Reclaimed Surface Coal Mine Spoil Aquifer Using MODFLOW. In Proceedings of the International Land Reclamation and Mine Drainage

Conference and Third International Conference on the Abatement of Acidic Drainage, Pittsburgh PA, Vol. 2, pp. 265-272.

Hawkins, J. W. and W. W. Aljoe, 1991. Hydrologic Characteristics of a Surface Mine Spoil Aquifer. In Proceedings of the Second International Conference on the Abatement of Acidic Drainage, Montreal, Quebec, Canada, Tome 1, pp. 47-68.

Hawkins, J.W. and W.W. Aljoe, 1990. Hydrologic Characterization and Modeling of a Heterogeneous Acid-Producing Surface Coal Mine, Upshur County, West Virginia, In the Proceedings of the 1990 National Symposium on Mining, May 14-18, 1990, University of Kentucky, Lexington Kentucky, pp. 43-52.

Hawkins, J.W., K.B.C. Brady, S. Barnes, and A.W. Rose, 1996, Shallow Ground Water Flow in Unmined Regions of the Northern Appalachian Plateau: Part 1. Physical Characteristics, In the Proceedings of the Thirteenth Annual Meeting of the American Society for Surface Mining and Reclamation, Knoxville, TN, pp. 42-51.

Helgeson, J. O. and A. C. Razem, 1980. Preliminary Observation of Surface-Mine Impacts on Ground Water in Two Small Watersheds in Eastern Ohio. p. 351-360. In Proceedings of the Symposium of Surface Mining Hydrology, Sedimentology and Reclamation. (Lexington, KY, December 1-5, 1980).

Hellier, W.W., 1998. Abatement of Acid Mine Drainage by Capping a Reclaimed Surface Mine with Fluidized Bed Combustion Ash, *Mine Water & the Environment*, Jour. of the International Mine Water Assoc., v. 17, no. 1, pp. 28-40.

Herring, W. C., 1977. Ground Water Re-Establishment in Cast Overburden. In Proceedings of the Seventh Symposium on Coal Mine Drainage Research, Louisville, KY, pp. 77-87.

Jorgensen, D. W. and T. W. Gardner, 1987. Infiltration Capacity of Disturbed Soils: Temporal Change and Lithologic Control. *Water Resources Bulletin*, v. 23, no. 6, pp. 1161-1172.

Kentucky, Natural Resources and Environmental Protection Cabinet, Division of Water and University of Kentucky Agronomy Department, March 1996. *Kentucky Coal Mining Practice Guidelines for Water Quality Management*.

Lundgren, T. and L. Lindahl, 1991. The Efficiency of Covering the Sulphidic Waste Rock in Bersbo, Sweden, Hydrologic Characteristics of a Surface Mine Spoil Aquifer. In Proceedings of the Second International Conference on the Abatement of Acidic Drainage, Montreal, Quebec, Canada, Tome 3, pp. 239-255.

Maryland Department of Natural Resources Bureau of Mines, *Technical Handbook for Mine Drainage Control Structures*, February 1989.

Meek, F. A., 1994. Evaluation of Acid Prevention Techniques Used in Surface Mining. In the Proceedings of International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage, v. 2 of 4, U.S. Bureau of Mines Special Publication SP 06B-94, pp. 41-48.

Miller, J.T. and D.R. Thompson, 1974. Seepage and Mine Barrier Width, In the Proceedings of the Fifth Symposium on Coal Mine Drainage Research, National Coal Association, Louisville, KY, pp. 103-127.

Nawrot, J.R., Sandusky, J. and Klimstra, W.B., 1988. Acid soils reclamation: applying the principles. In: Process Mine Drainage and Surface Mine Reclamation Conf., Pittsburgh, PA, April 1988. US Bureau of Mines and Office of Surface Mining Reclamation and Enforcement, pp. 93-103.

Olyphant, Greg A. and Harper, Denver. Effects of direct revegetation on the hydrology, erosion and sediment yield of an abandoned deposit of coal-mine refuse. *Geomorphology* 11 (1995) pp. 261-272.

Office of Surface Mining Guidelines for the Use of the Revised Universal Soil Loss Equation (RUSLE), Version 1.06 on Mined Land, Construction Sites and Reclaimed Lands, August 1998.

Pennsylvania Department of Environmental Protection, 1998. Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania, Brady, K.B.C., M.W. Smith, and J. Schueck, eds.

Pennsylvania Department of Environmental Protection, Bureaus of Mining and Reclamation and District Mining Operations, Engineering Manual for Mining Operations, 1999.

Potter, K. N., F. S. Carter, and E. C. Doll, 1988. Soil and Water Management and Conservation. *Soil Science Society of America Journal*. v. 52. pp. 1435-1438.

Rasmuson, A. and I. Neretnieks, 1986, Radionuclide Transport in Fast Channels in Crystalline Rock, *Water Resources Research*, Vol. 22, No. 8, pp. 1247-1256.

Razem, A. C., 1983. Ground Water Hydrology Before, During, and After Coal Strip Mining of a Small Watershed in Coshocton County, Ohio. U.S. Geological Survey, Water-Resources Investigation Report 83-4155. Columbus, OH. 36 p.

Razem, A. C., 1984. Ground Water Hydrology and Quality Before and After Strip Mining of a Small Watershed in Jefferson County, Ohio. U.S. Geological Survey, Water-Resources Investigation Report 84-4215. Columbus, OH. 39 p.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., and Yoder, D.C., 1997. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). USDA, Agriculture Handbook Number 703, 401p.

Rogowski, A. S. and H. B. Pionke, 1984. Hydrology and Water Quality on Stripmined Lands. U.S. Environmental Protection Agency, EPA-IAG-D5-E763, 183 p.

Silburn, D. M. and F. R. Crow, 1984. Soil Properties of Surface Mined Land. In Transactions of the ASAE, v. 27. no. 3. St. Joseph, MI, pp. 827-832.

Skousen, J., R. Hedin, and B. Faulkner, 1997, Water Quality Changes and Costs of Remining in Pennsylvania and West Virginia, In the Proceedings of the 1997 National Meeting of the American Society for Surface Mining and Reclamation, Austin, TX, pp. 64-73.

Smith, M. W., 1988. Establishing Baseline Pollution Load from Pre-existing Pollutational Discharges for Remining in Pennsylvania. Proceedings Mine Drainage and Surface Mine Reclamation Vol. II: Mine Reclamation, Abandoned Mine Lands and Policy Issues. U.S. Bureau of Mines IC 9184. Pittsburgh, PA. pp. 311-318.

Strock, N., 1998. Reclamation and Revegetation, Chapter 12 of Coal Mine Drainage Prediction and Pollution Prevention in Pennsylvania. Pennsylvania Dept. of Environmental Protection.

U.S. EPA, Office of Water, Municipal Wastewater Management Fact Sheets Storm Water Best Management Practices (EPA 832-F-96-001), September 1996.

U.S. EPA, Office of Water, Storm Water Management for Construction Activities, Developing Pollution Prevention Plans and Best Management Practices (EPA 832-R-92-005), September 1992.

U.S. Environmental Research Service, 1998. Engineered Structures for Sealing Underground Mines, Unpublished report prepared for West Virginia Surface Mine Drainage Task Force.

Weiss, J. S. and A. C. Razem. 1984. Simulation of Ground Water Flow in a Mined Watershed in Eastern Ohio. GROUND WATER, v. 22, no.5, p.549-560.

Wunsch, D. R. and J. S. Dinger. 1994. The Hydrogeology and Hydrogeochemistry of the Star Fire Site, Eastern Kentucky, In Proceedings of the International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage, Pittsburgh PA, Vol. 2, pp. 188-197.

Wyrick, G.G. and J.W. Borchers, 1981. Hydrologic Effects of Stress-Relief Fracturing In and Appalachian Valley, U.S. Geological Survey Water-Supply Paper 2177, pp. 51.

Yanful, E. K., B. C. Aube, M. Woyshner, and L. C. St-Arnaud, 1994. Field and Laboratory Performance of Engineered Covers for the Waite Amulet Tailings, In the Proceedings of International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage, v. 2 of 4, U.S. Bureau of Mines Special Publication SP 06B-94, pp. 138-147.

Zipper, C. E., T. Younos, and E. Yagow, Comparative Effects of Alternative Re-mining and Reclamation Strategies on Erosion Potential at a Case Study Abandoned Mine Land Site, 1992 National Meeting of the American Society for Surface Mining and Reclamation, Duluth, MN. pp. 671-679.

